EFFICIENT SERVICE CHANNEL UTILIZATION IN MULTICHANNEL VEHICULAR AD HOC NETWORKS

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EFFICIENT SERVICE CHANNEL UTILIZATION IN MULTICHANNEL VEHICULAR AD HOC NETWORKS

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CHAPTER I

INTRODUCTION

Vehicular ad-hoc networks (VANETs) have received much attention in both academia and industry. The importance of VANETs has been recognized due to their safety applications. For this purpose, vehicles equipped with Dedicated Short Range Communication (DSRC) devices periodically broadcast a basic safety messages (BSMs) that contain speed, acceleration, direction, GPS coordinates, and other useful information about the vehicles themselves. Other vehicles equipped with DSRC devices receive and process those BSMs for various security-related applications. For example, these BSMs can be used to predict the location of moving vehicles nearby and thus can be of value in collision avoidance. Furthermore, the vehicles can also transmit large size of data such as multimedia messages (e.g., audio, video.) for non-safety applications.

Wireless access in vehicular environments (WAVE) standards consist of the IEEE 802.11p and the IEEE 1609 family of standards. The IEEE 1609.4 out of the IEEE 1609 family describes the multi-channel architecture. According to the standard, there is one 10 MHz-wide control channel (CCH) for control and safety applications and six 10 MHz-wide service channels (SCHs) for non-safety applications [2] as shown in Figure 1. The CCH starts first, and it is followed by one of six SCHs. A sequence of CCH and SCH alternates every 50ms. During the CCH interval, every vehicle broadcasts its BSM, but optionally if a vehicle (called a service provider) intends to provide a specific service during the next SCH interval, it must broadcast its WAVE Service Advertisement (WSA) message in addition to its BSM. The WSA message contains the service and channel information, and any vehicle that wants the service (called a service user) can connect to the service provider by tuning to the indicated SCH during the SCH interval [1].

As shown in Figure 1, six SCHs (a total of 60 MHz) occupy 80% of the DSRC bandwidth of 75 MHz and utilize 50% of the time for the multi-channel operation. In addition, the Federal Communications Commission (FCC) permits WAVE systems deployed in the U.S. to use two SCHs (CH.172 and CH184) for public safety applications as well [12]. Therefore, the efficient utilization of the SCHs is as crucial as that of the CCH to enhance the performance of VANETs.

In this dissertation, an efficient SCH utilization method is presented for service providers to be able to broadcast their services to as many vehicles in a transmission range as possible. One of the major degrading factors especially in the broadcast scenario is the hidden terminal problem, which is any vehicles located in the areas of intersection within the range of transmission cannot decode messages that are simultaneously transmitted by vehicles that are out of each other's region. It is verified that the hidden terminal problem reduces the packet reception ratio in broadcast scenario [9]. However, there is lack of work that strives to mitigate the hidden terminal problem for broadcast transmission in the IEEE 1609.4 multi-channel environment. In this environment, the hidden terminal problem occurs when a service provider selects the same SCH as that of another hidden service provider. Moreover, the current standard does not specify how a service provider avoids selecting the same SCH as nearby hidden service providers, it is necessary to find a new method to ensure that a service provider does not select the same SCH while other hidden service providers chose the same SCH in the service channels. On the other hand, this proposed algorithm provides a service provider with information about which SCHs are selected by its hidden service providers before it broadcasts its WSA message so that it can avoid selecting the same SCH as nearby hidden service providers had already selected. Theoretical analysis and extensive simulation results verify that our novel algorithm contributes to performance enhancement in broadcast scenarios under the IEEE 1609.4 multi-channel environment. The proposed algorithm improves the packet reception ratio by 23% over the random SCH selection method.

Following the broadcast scenario, this dissertation focusses also on unicast transmission in the IEEE 1609.4 multi-channel environment. Unlike the CCH interval, during the SCH interval, the RTS/CTS/data/ACK handshake can be triggered to transmit large size of data without the hidden node problem. However, it can cause the exposed node problem that hinders concurrent transmissions, which is fatal in highly dynamic VANETs. Even though judicious SCH selection in a multi-channel environment can mitigate the exposed node problem, IEEE 1609.4 does not specify how to select a SCH, which can cause the randomly selected SCHs to be biased. Without modifying the current standards, this thesis therefore proposes a novel scheme that enables the exposed vehicles to avoid selecting the same SCH by piggybacking a *candidate* SCH selection into the optional field of the basic safety message. Through extensive simulations, it is verified that the average throughput can be improved by up to 26%.

Building upon the unicast scenario using the omnidirectional antenna, this dissertation further developed the unicast transmission using the directional antenna. When a large amount of data is transmitted in unicast, it is waste of energy to broadcast the data toward all the directions using omnidirectional antennas, which can also increase unnecessary interference to other vehicles. However, if directional antennas are utilized, a service provider can narrow down the beamwidth of the directional antenna and focus only on its target vehicle with higher data rate.

To the best of the knowledge, few research attempted to solve the directivity coordination problem in the IEEE 1609.4 multi-channel environment. Moreover, most existing directional MAC protocols depend upon the model of an ideal directional antenna that assumes the side lobe gain power to be zero, which is unrealistic. Consequently, their protocols cannot guarantee the expected performance in practice.

Therefore, this proposed solution considers the realistic directional antennas with non-negligible side lobe gain power. The directional antenna environment necessities the angle information between two vehicles to compute the signal-to-interference-plus-noise ratio (SINR) value. This proposed method piggybacks the beamforming direction information of the directional antenna into the BSM so that service providers can obtain both the SCH number and direction information. The service provider/user pair that has the lower SINR value than threshold SINR is categorized as interfering pair (*I*-pair). The service provider *T* selects the SCH number that has the least number of *I*-pairs. If the number of *I*-pairs are tied at multiple SCHs, then the maximizing sum rate optimization algorithm is performed.

The proposed solution is compared with other possible approaches: the least congested SCH selection method and the random SCH selection method. Theoretical analysis and extensive simulation results demonstrate that this proposed method outperforms the two schemes. As a result, this proposed directional MAC protocol can improve the wireless network capacity by maximizing the spatial reuse and minimizing the interference.

This dissertation is organized as follows: Chapter II provides background and related research. Chapter III details the efficient service channel utilization method for broadcast in the IEEE 1609.4 vehicular ad hoc networks. Chapter IV develops the protocol and algorithm of Chapter III for unicast scenario. Chapter V furthers the unicast transmission of Chapter IV and expands it to the directional antenna environment. Chapter VI states conclusions and future research.

CHAPTER II

BACKGROUND AND RELATED RESEARCH

2.1 Overview of the IEEE 1609.4 multichannel VANETs

Vehicular ad-hoc networks (VANETs) technology realizes vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, which can improve tremendously the quality of human lives in terms of safety and non-safety. For safety, every vehicle can periodically broadcast its basic safety message (BSM) that includes its location, direction, acceleration, and also other optional information [3]. By exchanging the neighboring vehicles' status information, vehicles can avoid collisions. For non-safety, vehicles can send large size multimedia data (e.g., audio or video) for infotainment to either one particular vehicle or all the neighboring anonymous ones.

To keep pace with the rapid advancement of technology in academia and industry, the Federal Communication Commission (FCC) allocated 75 MHz of spectrum in the band of 5.9 GHz for Dedicated Short Range Communications (DSRC) applications [1]. In addition, standard organizations such as the IEEE or the Society of Automotive Engineers (SAE) contribute to forming the rules for the interoperability between devices produced by different companies [3].

The physical and MAC layer protocols of the IEEE 802.11p standard are specified for single-channel operations [11]. However, since seven channels are available in DSRC spectrum, the IEEE standard specified multi-channel operations in the IEEE 1609.4 standard to enable a single radio device to access multi-channels in DSRC spectrum [6].

Wireless access in vehicular environments (WAVE) standards consist of IEEE 802.11p and the IEEE 1609 family of standards. The IEEE 1609.4 out of the IEEE 1609 family describes the multi-channel architecture. According to the standard, there is one 10 MHz-wide control channel (CCH) for control and safety applications and six 10 MHz-wide service channels (SCHs) for non-safety applications [1] as shown in Figure 1.

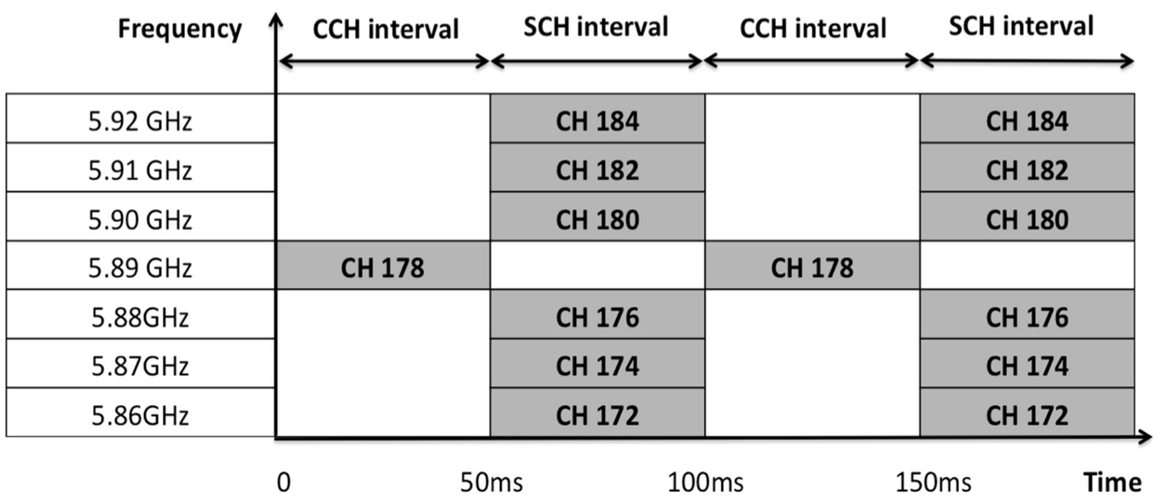


Figure 1: Illustration of the Multi-channel WAVE architecture

The CCH starts first, and it is followed by one of six SCHs. A sequence of CCH and SCH alternates every 50ms. During the CCH interval, every vehicle broadcasts its BSM, but optionally if a vehicle (called a service provider) intends to provide a specific service during the next SCH interval, it must broadcast its WAVE Service Advertisement (WSA) message in addition to its BSM. The WSA message contains the service and channel information, and any vehicle that wants the service (called a service user) can connect to the service provider by tuning to the indicated SCH frequency during the SCH interval [6]. As shown in Figure 2, six SCHs (a total of 60 MHz) occupy 80% of the DSRC bandwidth of 75 MHz and utilize 50% of the time for the multi-channel operation. In addition, the FCC permits WAVE systems deployed in the U.S. to use two SCHs (CH.172 and CH184) for public safety applications as well [1]. Therefore, the efficient utilization of the SCHs is as crucial as that of the CCH to enhance the performance of VANETs.

Accurate multi-channel operations necessitate time synchronization among multiple vehicles. Multiple vehicles can synchronize the CCH and SCH intervals to the Coordinated Universal Time (UTC) by the GPS. If the UTC is not available, a vehicle can get time information from WAVE Time Advertisement (WTA) frame that is transmitted by other vehicles [10].

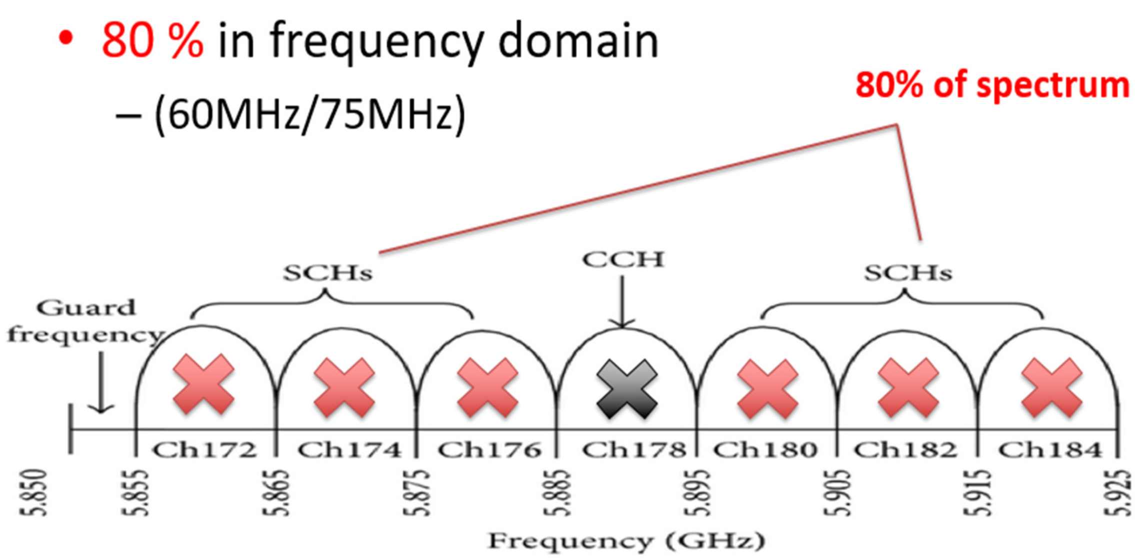


Figure 2: The ratio of service channel in DSRC spectrum

2.2 Related Research

2.2.1 MAC Protocols for Hidden node problem

The physical and MAC layer protocols of the IEEE 802.11p standard are specified for single-channel operations [11]. However, since seven channels are available in DSRC, the IEEE standard specified multi-channel operations in the IEEE 1609.4 standard to enable a single radio device to access multi-channels in DSRC spectrum [6]. Accurate multi-channel operations necessitate time synchronization among multiple vehicles. Multiple vehicles can synchronize the CCH and SCH intervals to the Coordinated Universal Time (UTC) by the GPS. If the UTC is not available, a vehicle can get time information from WAVE Time Advertisement (WTA) frame that is transmitted by other vehicles [10].

Zhang et al. [13] proposed a new multi-channel MAC protocol for IEEE 802.11p and IEEE 1609.4 to improve the packet delivery ratio during the CCH and throughput during the SCH. Their method integrates the time division multiple access (TDMA) and the carrier sense multiple access (CSMA) to broadcast the safety-related packets reliably and to mitigate the hidden terminal problem. They focused on inventing a new MAC protocol to improve performance in VANETs.

Lu et al. [14] presented another multi-channel MAC protocol to broadcast safety message without collision. Their MAC protocol enables the CCH interval to have a varying TDMA length to adapt itself to diverse traffic situations. They proved that their MAC protocol has higher packet delivery ratio of safety message than WAVE MAC protocol.

Sjöberg et al. [9] showed that the presence of hidden terminals drops the packet reception ratio (PRR) in both CSMA and self-organizing time division multiple access (STDMA) MAC protocols in a broadcast scenario. They demonstrated that STDMA has higher PRR than CSMA does because the synchronization of the STDMA MAC protocol protects the network system against the hidden terminal problems better than CSMA. However, their scenario is not under the IEEE 1609.4 multi-channel environment.

Zhang el al. [5] designed a distributed MMAC protocol to coordinate channel access at low control overhead. Multi-channel hidden terminals can be prevented by split-phase MMACs because they can negotiate channel on a default control channel. Their protocol combats hidden terminal problems by eliminating out-of-band and in-band control signaling. However, their main focus is not a broadcast scenario.

Wang et al. [4] suggested a variable CCH interval (VCI) multi-channel MAC protocol to utilize channel efficiently under WAVE systems. Their method adapts the length proportion between CCH and SCH in a synchronization interval. Their method increased the saturated throughput of SCHs but also gave priority to transmit critical safety messages during CCH. According to their method, however, additional packets such as variable control channel interval (VCI) packets, request for service (RFS) packets, and acknowledgement (ACK) packets must be additionally transmitted during each CCH interval. For instance, VCI packets must be broadcasted for safety message transmission. Service users must reply to the WSA message with an ACK if service providers broadcast WSA messages. A service user must send an RFS packet, and an ACK packet must be sent to respond to the RFS packet.

However, few studies have shown how the unique IEEE 1609.4 multi-channel operations affect the hidden terminal problems of broadcast scenarios in VANETs without any modifications of WAVE MAC protocol.

2.2.2 MAC Protocols for Exposed node problem

2.2.2.1 Single Channel environments

There has been substantial research about the exposed node problems in single channel environments. Jayasuriya et al. [17] analytically proved that the exposed nodes degrade the network throughput more than the hidden nodes do under the handshake mechanisms such as RTS/CTS. Shukla et al. [26] improved overall throughput by minimally modifying the IEEE 802.11 DCF MAC protocol. According to their opportunistic algorithm, nodes that identify themselves as exposed nodes can transmit in parallel while there is an ongoing data transmission. Jiang et al. [18] proved that nonscalable throughput results from exposed nodes rather than hidden nodes. They invented their MAC protocol called Selective Disregard of Network Allocation Vectors (SDN), which totally removes exposed nodes and obtains network throughput scalability. Wang et al. [19] presented a cross-layer design to solve both the hidden and the exposed node problems using a PHY layer attachment coding and a MAC layer attachment sense. Yao et al. [20] proposed an Interference Resistant Multiple Access (IRMA) scheme, which updates the Network Allocation Vector (NAV) information in the MAC layer. They showed that the IRMA can obtain higher throughput than the 802.11 standard.

Since these protocols are designed for a single channel, they can be used when several service providers cannot avoid using the same SCH because there are many more service providers than available channels. In other words, these protocols are compatible with the proposed protocol. Since the IEEE 1609.4 standard operates in the higher layer than the layer defined by the IEEE 802.11p, the proposed protocol can coexist with any 802.11p MAC layer protocols.

2.2.2.2 Multichannel environments

Many studies also aimed (explored) to solve the exposed node problems in multi-channel environments. Wu et al. [32] designed a multi-channel MAC protocol to mitigate the exposed node problem in multihop wireless networks. According to their channel selection scheme, data packets can be transmitted in a conflict-free channel while RTS/CTS packets in a common channel. Since their protocol enables the ACK packet to be transmitted in another common channel, the consequence of the exposed node problem can be mitigated. Their protocol, however, can be applied when there are two separate CCHs, which is a critical limitation in typical IEEE 802.11p/1604 multi-channel environments where only one CCH is utilized.

Nguyen et al. [23] presented an e-VeMAC protodol, in which they modified the VeMAC protocol [22, 24] to promote more parallel transmission to mitigate the exposed node problem. They showed that during the CCH interval, their protocol can reduce the number of nodes that rebroadcast a packet in parallel transmission, compared to the VeMAC protocol. However, their protocol has the limitation that it can be applied to only the TDMA-based MAC protocol. Besides, they did not demonstrate whether or not their protocol could improve the performance for dynamically moving vehicles in urban or highway scenarios.

Zhang et al. [5] invented their own protocol called FD- MMAC to solve the hidden and exposed node problems in a single radio and multi-channel environments. Chakraborty et al. [59] also reduced the hidden and exposed nodes for mesh networks, but their main focus is not 1609.4 multi-channel environments.

2.2.3 MAC Protocols for Directional Antennas

The classification of directional antenna is surveyed by Dai et al. [56]. The directional antenna can be classified as follows:

- Traditional directed antennas
    - The beamforming is fixed
    - The beam can be formed to a certain direction by mechanically rotating the antenna
- Smart antennas
    - Switched beam antenna
        - The beam patterns of the antenna are predetermined. The desired beam pattern can be instantaneously switched.
    - Steering single beam antenna
        - The beam patterns of the antenna are formed arbitrarily. The beam pattern can be directed to a target but also can be null towards interference.
    - Adaptive array antenna
        - The beam patterns of the antenna can be dynamically formed and can receive multi-path signals adaptively.

Choudhury et al. [33] designed medium access control protocol for directional antennas (DMAC) to increase spatial reuse. Their MAC protocol is based on IEEE 802.11 MAC so it assumes CSMA/CA and exploits RTS/CTS/data/ACK handshake and the network allocation vector (NAV) concepts. They showed their MAC protocol outperforms IEEE 802.11 depending on the topology configuration. However, they assumed the directional antenna gain of the side lobes is very low. Kuperman et al. [34] proposed MAC policies for fully digital antenna arrays to communicate with adaptive multi-beam. The fully digital beamforming is different from the conventional beamforming that schedules a beam direction to the transmitter. However, their MAC policy uses an un-slotted and un-coordinated ALOHA-like random access, which cannot be applied to CSMA/CA environments.

Lu et al. [35] considered a dedicated multi-channel MAC (DMMAC) protocol that combines the advantages of TDMA and CSMA/CA for reliable safety message transmission. Their MAC protocol can reduce collision and delay. However, they focused on only broadcasting. Dai et al. [36] presented a multi-channel multiple directional antennas (MC-MDA) network architecture. They exploit the characteristics of the multi-channel and multiple directional antennas to increase spatial reuse and improve the network capacity. They also derived the upper and lower bounds of the wireless network capacity. They concluded the MC-MDA networks mitigate the network interference. Zhang et al. [51] analyzed the end-to-end throughput per node in the single channel wireless mesh networks. They proved that using directional antennas can improve the single channel wireless network capacity. Ulukan et al. [37] considered Angular MAC (ANMAC) protocol for multibeam antennas. that needs to keep the location information of other nodes.

Their protocol assumes that every node has four-90^o beams to cover 360^o, which forces every node to have four directional antennas.

Hadjadj et al. [38] considered the hidden node and deafness problems under directional antennas environments. They changed the settings to the directional NAV (DNAV) to handle the arrival of corrupted packets and the noise. However, their protocol necessities to transmit the CTS packet directionally to the deaf nodes to retransmit the RTS packets. Bazan et al. [39] remedied the limitation of the traditional binary exponential backoff mechanism and proposed an opportunistic directional MAC (OPDMAC) protocol. They designed their backoff mechanism that prevents a node that failed transmission from mandatory idle backoff. The OPDMAC increases the wireless medium utilization by minimizing the idle backoff time without additional overhead. However, they have not considered mobility. Therefore, their protocol is more applicable to static topologies such as mesh networks rather than mobile or vehicular ad-hoc networks. Kwon et al. [40] considered the overhead, the multi-rate, and the asymmetric-in-gain problems in using directional antennas, and presented a directional cooperative MAC (DC-MAC) protocol that delivers data via a relay node. However, they used the flat-top directional antenna [41], which assumes the side lobe gain power to be zero. Abdullah et al. [42] stated the dual-sensing directional MAC (DSDMAC) protocol for directional antennas in multi-hop wireless ad hoc networks.

Niu et al. [47] designed a fully-distributed directional-to-directional MAC (FDD-MAC) protocol that assumes only directional antennas operate. They attempt to mitigated the deafness problem using their asynchronous protocol. However, they did not consider the pathloss and the directional antenna gain in their protocol. Tyagi et al. [48] first addressed diverse factors that affect the deafness problem in wireless ad hoc networks using directional antennas. Masri et al. [49] considered the fairness in their MAC protocol and presented a synchronized-based MAC protocol for fair bandwidth utilization in wireless mish networks using beamforming antennas. Wu et al. [50] proposed an apprenticeship learning based spectrum decision method in directional wireless mesh networks using multi-channel and multi-beam directional antennas. The scheme considered the channel quality, link load, node location, beamforming orientation, interference, and deafness for channel assignment and handoff. Their algorithm effectively utilizes both the spatial and frequency separation for channel selection. Ren et al. [52] studied the multicast capacity of vehicular ad hoc networks using directional antenna.

Georgiou et al. [53] investigated how the direction of antenna can affect the connectivity of the network. They showed that if the antenna gain of a receiver is towards a sender and sway from potentially interfering nodes, the ad hoc networks can be improved by the interference isolation.

Dang et al. [54] considered directional MAC protocol in multi-channel environments and presented a multi-channel MAC protocol with directional antennas (MMAC-DA). Their protocol showed the directional antennas with multi-channel resources increased concurrent data transmission. However, they did not address the effect of the gain power of the side lobes of the directional antenna in their MAC protocol.

However, those MAC protocols for directional antenna do not consider the interference of the side lobes by assuming that the directional antenna is ideal. The directional antenna that they have used is divided ideally. The antenna has a constant gain power toward all directions inside the sector and zero power outside the designated sector, which is not realistic. Several studies also used flat-top antenna model that assumes to have a constant gain at all the directions inside the sector, which is impossible for any physical antennas. Therefore, those protocols cannot guarantee the performance in practice. Takai et al. [46] addressed that some unwanted frames from other neighbor nodes can collide with the receiving frames through the main lobe.

Takatsuka et al. [44] showed that the interference of side and back lobes of a practical antenna is not negligible. Their proposed protocol rotates the receiving beams of the directionally antenna to mitigates the interference by the side and back lobes. Chang et al. [45] detailed the problems caused by the minor-lobe and proposed a reservation-based directional MAC (RDMAC) protocol based on the IEEE 802.11 DCF. Wang et al. [43] proposed a cooperative multi-channel directional MAC (CMDMAC) protocol by incorporating directional antenna and multi-channel transmission. They considered the minor lobe interference problems in their directional MAC protocol under multi-channel environments. They compared the case that the minor lobe interference is considered with the case of the ideal antenna that assumes the minor lobe gain power is zero.

CHAPTER III

SCH utilization scheme for IEEE 1609.4 multichannel environments in VANETs

The main goal of this chapter is to investigate novel method to utilize the service channel for the IEEE 1609.4 multi-channel environments in VANETs. In the following sections, the proposed protocol and algorithm for broadcast scenarios will be explained in details [15].

3.1 Introduction

The current IEEE 1609.4 standard defines multi-channel operations to alternate control and service channel intervals during a period of 100ms. However, there is no mention of service channel selection for a service provider, which allows hidden service providers to select the same service channel (SCH). This limitation can cause the hidden terminal problem during the SCH intervals, leading to significant performance deterioration. Without modifying the existing standards, the proposed scheme enables hidden service providers to avoid selecting the same SCH by delivering their *candidate* service channel number in the optional field of the basic safety message (BSM). Through extensive simulations, it is verified that the packet reception ratio can be improved by up to 23% in typical broadcast scenarios.

3.2 Protocol and Algorithm for Broadcast scenario

3.2.1 Motivation

According to the IEEE 1609.4 standard, if a service provider intends to provide a specific service to prospective service users in a certain SCH, the service provider must broadcast its WSA message that contains a SCH number prior to the end of the current CCH. The SCH number can be any one of the six SCHs in the DSRC spectrum as shown in Figure 1. (e.g., CH.172, CH.174, CH.176, CH.180, CH.182, or CH.184). If any vehicle wants the service advertised by the service provider, that vehicle (the service user) must switch to the advertised SCH frequency in the beginning of that SCH interval.

However, the current standard does not specify how a service provider selects one of the six SCHs following the current CCH. Because there is no specific method to prohibit hidden service providers from selecting the same SCH, hidden service providers that select the same SCH can cause the hidden terminal problem and consequently degrade the performance during the SCH intervals. The hidden terminal problem is particularly fatal in broadcast scenarios since no acknowledgements (ACK) or RTS/CTS packets are expected. If hidden service providers can avoid selecting the same SCH number, the network system degradation caused by the hidden terminal problem will be significantly mitigated. Therefore, this dissertation suggests a novel approach that enables hidden service providers to avoid selecting the same SCH number in a broadcast scenario under the IEEE 1609.4 multi-channel environment.

3.2.2 Protocol Description

Conforming to the current standards, our proposed protocol exploits the unique characters of BSM and WSA message. The BSM consists of Part I (required) and Part II (optional) data frames [3]. The part I of the BSM includes mandatory elements, such as location, speed, direction, and acceleration. Part II of the BSM contains optional data elements and data frames. The BSM includes Part II when specific events are necessary. Therefore, the BSM is flexible to convey additional information. Even though the BSM size is variable, special efforts have been made to minimize the BSM size. The length of the WSA format is also variable and theoretically up to about 2000 bytes, depending on what is included [7]. The channel information of the WSA frame format contains the channel number as shown in Figure 3 [8].

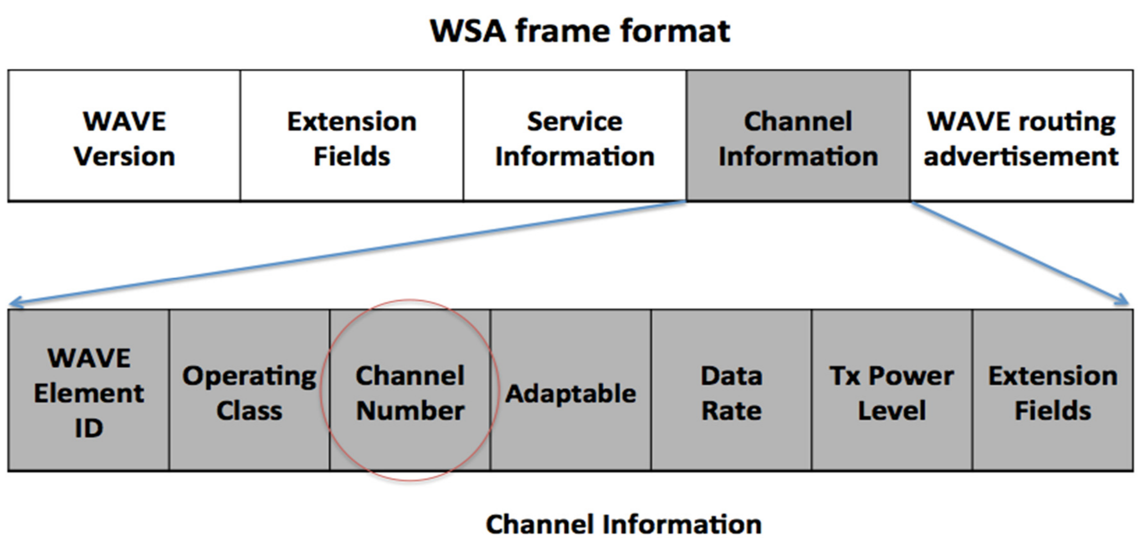


Figure 3: WSA Packet Format

The one-byte channel number information holds an integer representing seven 10 MHz-wide channel numbers of 172, 174, 176, 178, 180, 182, or 184 in the US DSRC [7].

Our novel protocol utilizes the optional elements in the Part II of the BSM to convey the SCH number information before broadcasting a WSA message. In this approach, three terms are defined as follows:

- *BSM_SP*: the BSM into which a service provider piggybacks the one-byte SCH number information.
- Intermediary receiver (*IR*): the receiver in the transmission range of two or more hidden service providers.
- *BSM_IR*: the alerting BSM broadcasted by an intermediary receiver only if it receives a *BSM_SP* that contains the same SCH number as a previous *BSM_SP*.

The roles of BSM_SP, Intermediary receiver, and BSM_IR are specified as follows:

1) *BSM_SP*: In the proposed protocol, a service provider broadcasts its BSM_SP before finally broadcasting its WSA message. The purpose of the BSM_SP is that a service provider can recognize whether other hidden service providers already selected the same SCH by broadcasting their BSM_SPs beforehand. Suppose that a service provider υ broadcasts its BSM_SP containing the SCH number, which is an element of a set Z = {172, 174, 176, 180, 182, 184}. If no service provider had broadcasted its *BSM_SP* with the same

SCH number α before υ did, the service provider υ can keep the SCH number.

However, if any service provider had already broadcasted its *BSM_SP* with the same SCH number, the service provider υ should avoid selecting the SCH number, and re-broadcast its *BSM_SP* containing different SCH number from α in a set Z. In addition, *BSM_SP* can contain more than one SCH number in a set Z.

2) Intermediary Receiver: The active role to broadcast the SCH number selection information of service providers is taken by the vehicle that can receive the *BSM_SPs* from two hidden service providers, which is the intermediary receiver as defined previously. Receiving BSMs that contain GPS information from two vehicles, the intermediary receiver is able to detect whether the two vehicles are hidden service providers in relation to each other. In our protocol, the intermediary receiver takes an alerting role in which it broadcasts which service provider selected a SCH number first.

Because all the vehicles including intermediary receivers receive and maintain information about all the BSMs they received, the intermediary receiver is able to extract which service provider first broadcasted its *BSM_SP* with a specific SCH number. Since the proposed protocol is on a first come first served basis, the service provider that first broadcasted its *BSM_SP* has priority to keep that SCH number and can finally broadcast its WSA indicating that SCH number.

3) *BSM_IR*: When intermediary receiver receives a *BSM_SP* that contains the same SCH number as a previous *BSM_SP*, it must broadcast an alerting BSM, which is defined as a *BSM_IR*. *BSM_IR* contains all the service providers' IDs and their selected SCH

numbers with time stamps. Therefore, hearing the *BSM_IR* from an intermediary receiver, a service provider can judge who first broadcasted the *BSM_SP* with the same SCH number. The intermediary receiver broadcasts the *BSM_IR* using a back off algorithm designed for IEEE 802.11p to avoid possible collisions among the other IRs, and the other IRs that once hear a *BSM_IR* do not broadcast their *BSM_IRs*.

3.2.3 Algorithm for service channel selection

This section introduces an algorithm to determine which SCH number a service provider will contain in the WSA message during the CCH interval. The algorithm is executed by service provider (see Algorithm 1).

Algorithm 1. Procedure in Selecting SCH Number

```
// Executed by a service provider during the CCH interval

// SCH_curr: current SCH number in BSM_SP
// SCH_next: updated SCH number in next BSM_SP
// WSA_sch_num: SCH number in WSA
// SCH_set: {172, 174, 176, 180, 182, 184}.
// SCH_bsm_ir: SCH numbers in BSM_IRs from IRs
// BSM_IR_num: total number of BSM_IRs from IRs

WSA_sch_num = NULL
Broadcast a BSM_SP with a SCH_curr
if BSM_IR_num = 0 then
  WSA_sch_num = SCH_curr
  Return
end if
Broadcast a BSM_SP with SCH_set - {SCH_curr}
if BSM_IR_num = 0 then
  SCH_next = random(SCH_set - {SCH_curr})
else
  SCH_next = random(SCH_set - {SCH_bsm_ir})
end if
  WSA_sch_num = SCH_next
```

A service provider broadcasts its *BSM_SP* with a specific SCH number. If no intermediary receiver broadcasts an alerting *BSM_IR*, the service provider wins that SCH number and can be prepared to broadcast its WSA message with that SCH number.

However, if any intermediary receiver broadcasts its alerting *BSM_IR* with that SCH number, the service provider should avoid that SCH number and broadcast the 2nd *BSM_SP* with all the remaining SCH numbers except the SCH number that it selected previously.

If no intermediary receiver broadcasts its alerting *BSM_IR*, the service provider selects one of that remaining SCH numbers and broadcasts the final *BSM_SP* with the SCH number it finally selected. Having heard the final *BSM_SP* broadcasted, intermediary receivers around the service provider will prevent prospective hidden service providers from selecting the same SCH number in the final *BSM_SP*.

However, if several intermediary receivers broadcast their alerting *BSM_IRs* corresponding to any of that remaining SCH numbers, the service provider should avoid that SCH numbers in the alerting *BSM_IRs* and select one of the left SCH numbers and broad the final *BSM_SP* with that SCH number.

3.2.4 Mathematical Analysis

In the IEEE 1609.4 multi-channel standard, if hidden service providers occupy the same SCH, the hidden terminal problem can occur. Suppose a vehicle υ is a service provider, and there are n numbers of SCHs and H numbers of hidden service providers abound the vehicle υ. $\Phi(n)$ is defined as the probability representing the case in which all the H number of hidden service providers around the υ select different SCHs from the SCH that the vehicle υ selects out of the n numbers of SCHs.

$$\Phi(n) \;=\; \frac{1}{n} * \left(\frac{n-1}{n}\right)^{H} * \; n \;=\; \left(\frac{n-1}{n}\right)^{H} \tag{1}$$

Let *ρ(n)* be the probability that the vehicle υ selects the same SCH as at least one of the SCHs that H hidden service providers select out of the n numbers of SCHs.

$$\rho(n) \;=\; 1 \;-\; \Phi(n) \;=\; 1 \;-\; \left(\frac{n-1}{n}\right)^{H} \tag{2}$$

If n, which is the number of available SCHs is infinite, the probability *ρ(n)* becomes zero.

$$\lim_{n\to\infty} \left(\frac{n-1}{n}\right)^{H} \;=\; 1 \tag{3}$$

$$\lim_{n\to\infty} \rho(n) = \lim_{n\to\infty} \left(1 \;-\; \left(\frac{n-1}{n}\right)^{H}\right) \;=\; 0 \tag{4}$$

Let ρ(n) be the probability that the vehicle υ selects the same SCH as at least one of the SCHs that H hidden service providers select out of the n numbers of SCHs.

In other words, the probability representing the case in which the service provider υ has at least one hidden service provider that can cause the hidden terminal problem becomes zero if there is an infinite number of SCHs.

Practically, however, the number of available SCHs is less than or equal to six. Therefore, as the number of hidden service providers around the vehicle υ, H increases, *ρ(n)* converges to one, which is the theoretical limitation of the random selection of the SCH. As the probability *ρ(n)* increases, consequently the probability of the hidden terminal problem occurring also increases. Therefore, if there is a method to decrease the value of *ρ(n),* the probability of the hidden terminal problem occurring will also decrease, eventually leading to performance enhancement.

If the service provider υ knew a specific SCH is already selected, υ will select another SCH out of the *(n-1)* numbers of SCHs. *ρ'(n)* is the probability that the service provider υ selects the same SCH again as at least one of the H numbers of hidden service providers around υ.

$$\rho'(n) = \left\{1 - \left(\frac{\mathrm{n}-1}{\mathrm{n}}\right)^{H}\right\} * \left\{1 - \left(\frac{n-2}{n-1}\right)^{H}\right\} = \rho(n) * \rho(n-1) \tag{5}$$

$$\rho'(n) < \rho(n) \tag{6}$$

Since the value of *ρ(n -1)* is always less than one, *ρ'(n) = ρ(n) * ρ(n -1)* is also always less than *ρ(n).* That is, if the service provider υ knew that one or more than one SCH(s) had already been selected, *ρ(n)* will decrease. The more SCH selection information the service provider υ knows, the more drastically $\rho(n)$ will decrease. Therefore, the knowledge of the SCH usage by other hidden service providers will definitely decrease the value of $\rho(n)$, leading to the mitigation of the hidden terminal problem.

3.3 Performance Evaluation

In this section, the performance of the proposed scheme is evaluated against the random SCH selection way. Details for the simulation environment are depicted with the results in the following sections.

3.3.1 Simulation Environment

To analyze the performance, the simulations are performed in a Network Simulator (NS-2), where the IEEE 1609.4 multi- channel architecture is implemented along with IEEE 802.11p. Every vehicle is equipped with DSRC device and is able to communicate over the seven 10 MHz channels. In the context of this paper, BSMs and WSAs during are broadcasted during the CCH intervals, and service users receive non-safety packets during SCH intervals.

To verify the efficiency of the proposed method in the real-world scenario, the number and type of vehicles are determined in a heterogeneous fashion on the roads in Hollywood, CA using SUMO [25]. λ is defined as a percentage of total vehicles performing the role of service providers, and the rest of the vehicles are service users. In addition, the results are obtained from the average of 100 simulation runs with 20% confidence interval.

TABLE 1: Simulation Parameters

Parameter	Value
Data Rate	3 *Mbps*
BSM packet size	100 *bytes*
Area	2*km* x 2*km*
Transmit range	250*m*
Number of Vehicles	80 – 200
Average Speed	50-55 mph
Number of SPs (λ)	25-30
Distribution	Heterogeneous
Mobility	OSM + SUMO
Fading	Nakagami
Simulation Time	200 *seconds*
Confidence Interval	20%

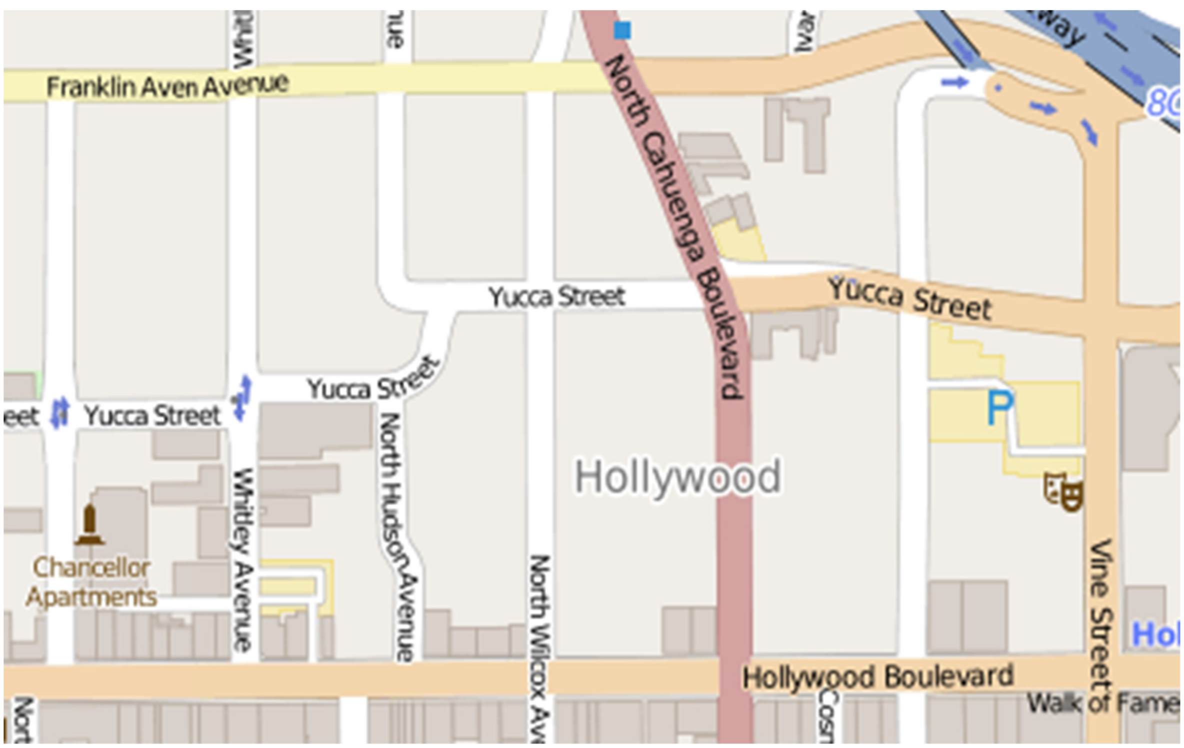


Figure 4: Traffic Trace Files, Hollywood Road, USA (SUMO)

3.3.2 Simulation Results and Analysis

In this sub-section, a quality metric called Packet Reception Ratio (PRR) is defined to compare and discuss the obtained results with other methods.

$$PRR = \frac{Total\ numbers\ of\ packets\ received}{Total\ numbers\ of\ packets\ sent} \tag{7}$$

First, in a static scenario where the vehicles stop due to traffic signal, intersection, traffic jam, or other reasons, the following case is considered: the number of service users is set to five, while the number of service providers increases. The five service users are uniformly distributed in the transmission range of a service provider. Hidden service providers around the service provider are randomly distributed. As shown in Figure 5, the PRR value of the random SCH selection method decreases as the number of service provider increases because the probability of selecting the same SCH increases as the number of service provider increases. This simulation result is expected as the theoretical analysis derived in Chapter III-3.4 verified the limitation of the random selection of the SCH. On the contrary, the proposed protocol enables service providers to avoid selecting the same SCH. Therefore, the PRR value is higher than that of the random SCH selection way. Figure 5 verifies that the proposed method outperforms the random SCH selection way. As proved in Chapter III-3.4, the knowledge of the SCH usage by other hidden service providers mitigated the hidden terminal problem.

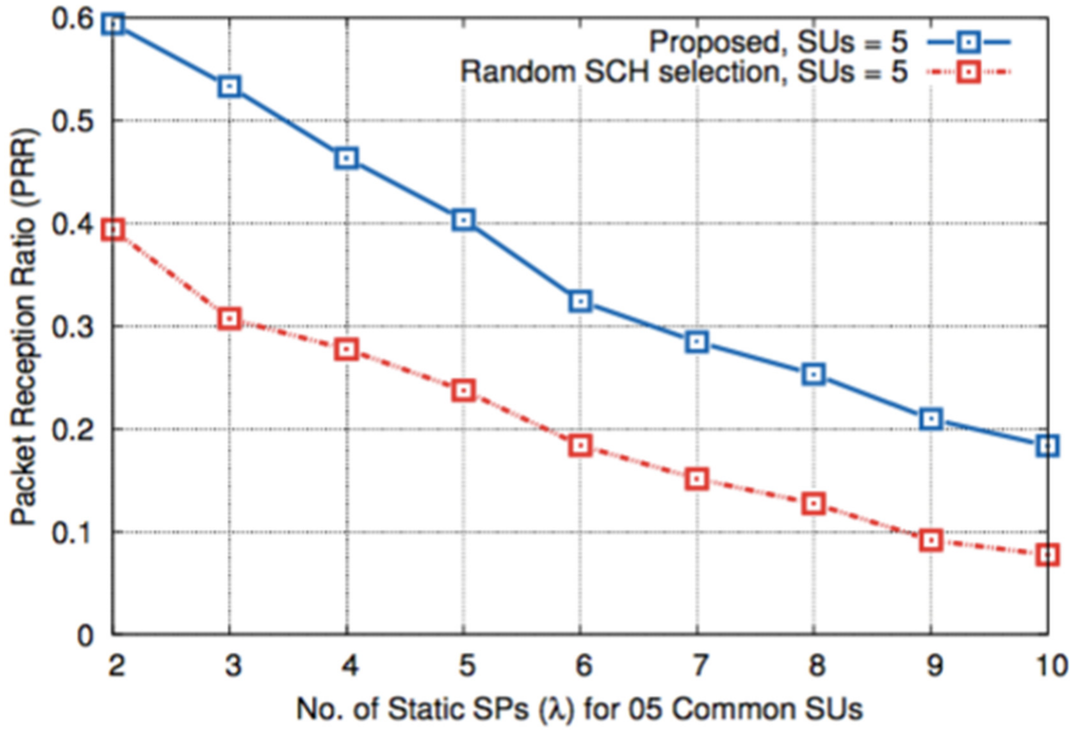


Figure 5: PRR vs Number of service providers (static scenario)

Secondly, a real moving scenario is also considered as shown in Figure 4. For the real moving scenario, the PRR is evaluated for the proposed protocol against the random SCH selection way. After each CCH interval, the SCH selection is randomly selected. Therefore, in case of hidden service providers, it is expected that service providers may opt for the same channel for the upcoming SCH interval using WSA messages. Due to the identical SCH, service users are vulnerable to a lot of service packets loss during the entire SCH interval. Evidently the simulation results show that the random SCH selection way has lower PRR than the proposed method, where we let intermediary receivers play a role of coordinators between hidden service providers. Through this coordination, a service provider is promptly informed about the already selected SCH and therefore, it can avoid selecting the same SCH. This novel SCH selection guarantees the higher PRR and reliable broadcast in the IEEE 1609.4 multi-channel environments.

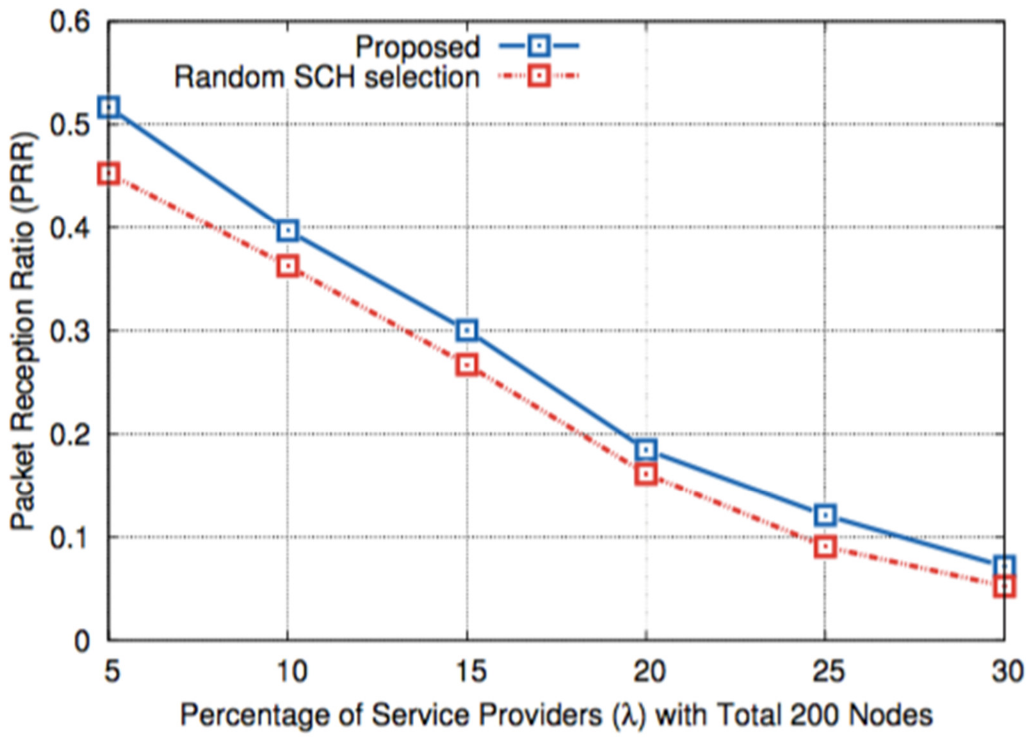


Figure 6: PRR vs Percentage of service providers (moving scenario)

The total number of service providers in both static and moving scenarios directly affects the overall performance. Therefore, this approach is evaluated in such a case, where the total number of vehicles is fixed, while the λ value is increasing. This approach can check the feasibility of the proposed scheme in case there is higher frequency of service providers around service users. Since the increasing number of service providers may trigger additional hidden terminal problems, it is noted that the PRR drastically goes down in both the random SCH selection and the proposed approach. However, it is depicted that the appropriate SCH selection still enables the proposed method to secure higher PRR consistently than that of the random SCH selection method in Figure 6. We calculated the average percentage difference between the random SCH selection one and the proposed approach. The proposed method has average 13% higher PRR value than that of random SCH selection one in Figure 6.

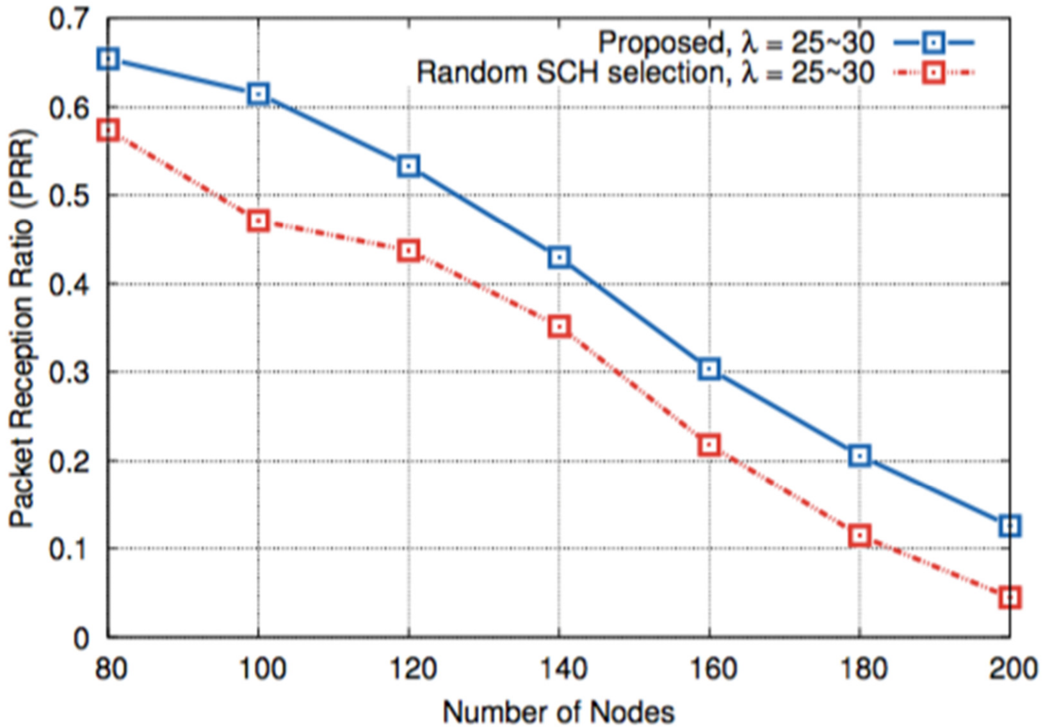


Figure 7: PRR vs Number of Service Provider (moving scenario)

The proposed approach is also compared in such a case, where the total number of vehicles increases and likewise the total number of service providers also increases. Since there are more service providers in the narrower distance, the more service providers in the closer distance compete for the limited numbers of SCHs, which consequently can cause hidden terminal problems. The PRR value of the proposed approach is higher than that of the random SCH selection one as shown in Figure 7. We calculated the average percentage difference between the random SCH selection one and the proposed approach. The proposed scheme has average 23% higher PRR value than that of random SCH selection one.

Since the proposed method sends additional BSM packets, the cost is faced in terms of overhead. It is calculated that the average BSM overhead generated during the CCH in the simulations.

$$\frac{\sum BSMs}{\sum Simulation\_Runs}$$

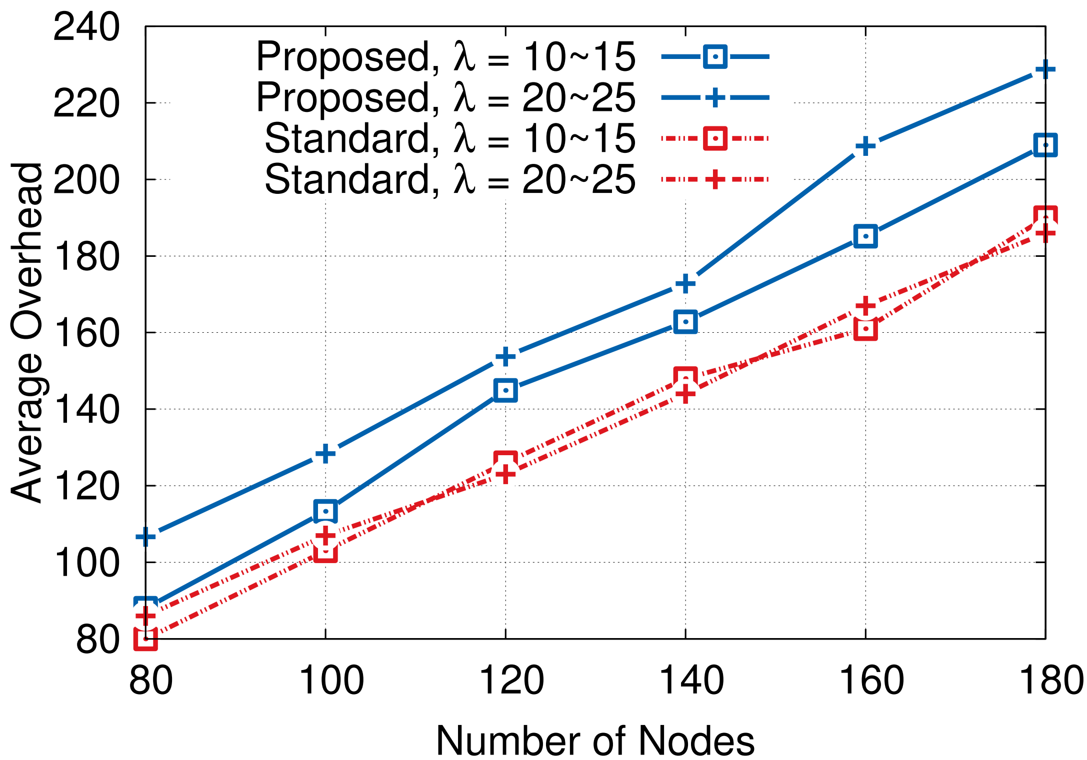


Figure 8: Average overhead vs Number of nodes

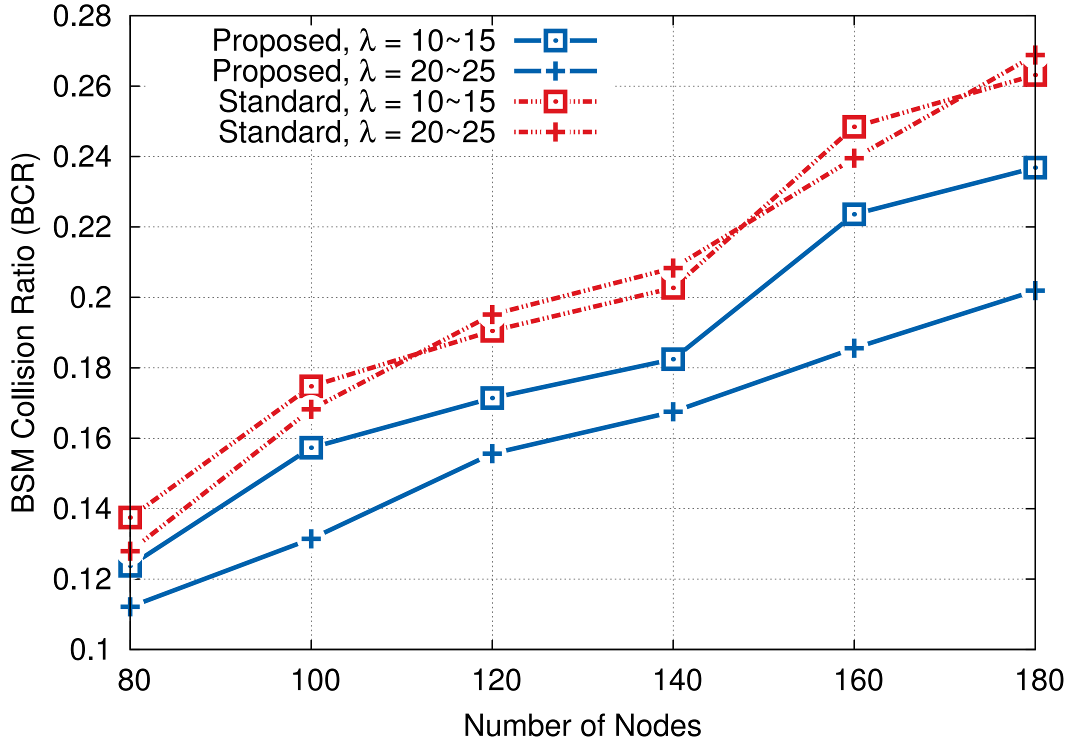


Figure 9: BSM collision ratio vs Number of nodes

BSM collision ratio (BCR) is defined as the number of BSMs collided over total number of BSMs generated. In standard, there might be a case when more than one node broadcast BSM at the same time, collision will occur. However, in the proposed work, by paying a minor cost of additional BSMs, less collisions on average is achieved. This shows that the proposed work also guarantees the updated BSMs being exchanged among neighbor nodes.

3.4 Conclusions

According to the current IEEE 1609.4 standard, a service provider broadcasts its WSA message that includes a SCH number to inform service users which SCH will be used. However, this method is unable to prohibit hidden service providers from using the same SCH, which will lead to the hidden terminal problem. We proposed a novel scheme that enables a service provider to avoid selecting the same SCH as nearby hidden service providers had already selected. We demonstrated that this proposed approach has average 13% to 23% higher packet reception ratio than the random SCH way in broadcast scenarios under the IEEE 1609.4 multi-channel environment.

CHAPTER IV

Distributed Service Channel Selection for concurrent transmissions

Following the previous Chapter III that focuses on the broadcast scenario, this Chapter presents a novel distributed service channel selection method for unicast scenario [16]. Conforming to the current standards, this Chapter proposes a novel scheme that enables the exposed vehicles to avoid selecting the same SCH. Through extensive simulations, it is verified that the average throughput can be improved by up to 26%.

4.1. Introduction

The Federal Communication Commission (FCC) allocated 75 MHz of spectrum in the band of 5.9 GHz for vehicle-to vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. The 75 MHz of Dedicated Short Range Communications (DSRC) spectrum is utilized to improve the quality of human lives in terms of safety and infotainment. For safety, every vehicle periodically broadcasts a basic safety message (BSM) that includes its location, direction, acceleration, and other optional information [3]. For infotainment, stationary roadside units (RSUs) that are connected to the internet via infrastructure are deployed along the roads. Thus the RSUs and vehicles can send large size multimedia data (e.g., audio or video) to each other for various applications. Because of deployment cost, however, the RSUs are generally separated at a significantly long distance between two nearby RSUs, which fails to provide seamless coverage. To overcome that limitation of V2I communications, much recent research has been conducted to extend the coverage range of the RSU by using V2V unicast communications [27,28,29]. However, the previous research has not considered the IEEE 1609.4 multichannel environment where communication channel intervals quickly alternate every 50 ms.

IEEE 1609.4 specifies multi-channel operations to enable a single radio device to efficiently utilize the seven channels in DSRC spectrum as shown in Figure 1 [1]. According to IEEE 1609.4, the control channel (CCH) and service channel (SCH) intervals alternate every 50 ms. The CCH is assigned for safety and coordination, and the six SCHs are for infotainment applications.

During the CCH interval, an RSU or a vehicle can be configured as a service provider if it broadcasts its WAVE Service Advertisement (WSA) message that advertises a typical multimedia service. The WSA message includes one particular SCH in which the advertised service will be provided during the SCH interval [1]. If a vehicle (called service user) hears the WSA message and intends to receive the advertised service, it must tune to that particular SCH in the following SCH interval. However, the current IEEE 1609.4 standard does not specify how a service provider selects the SCH number that is included in the WSA message.

During the SCH interval, if a service provider intends to unicast a larger size data than the preset RTS threshold size, it can perform the virtual carrier sensing such as RTS/CTS handshake to avoid the hidden node problems [11]. However, the RTS/CTS handshake results in the exposed node problem, which forces the nodes that hear RTS or CTS packets to defer their medium access until the RTC/CTS/data/ACK handshake ends. The exposed node problem is more fatal in VANETs than in MANETs because fast moving vehicles can go beyond the transmission range of each other even during the short time that they are forced to defer their transmission. In addition, the exposed node problem is proved to degrade the network performance more than the hidden node problem under the RTS/CTS handshake [17].

To the best of the knowledge, there is a lack of research that attempts to solve the exposed node problem in the IEEE 1609.4 multi-channel environment. Therefore, this chapter proposes a novel scheme that can mitigate the exposed node problem in the environment. Our proposed method enables a service provider to avoid selecting the same SCH number as other service providers, leading to concurrent transmissions. Thus the service providers do not defer their medium access because they are not in the same SCH. Our extensive simulation demonstrates that the proposed scheme improved the average throughput by up to 26%.

4.2. Protocol and Algorithm for Unicast scenario

This section introduces the problem definition and the design of the proposed protocol and algorithm.

4.2.1 Motivation

RSUs are expected to offer most DSRC services, but a vehicle (called a service provider) can also provide a service during the SCH intervals [1]. Even though virtual carrier sensing such as RTS/CTS handshake is not used during the CCH interval for reliable safety message broadcasting, it can be triggered during the SCH interval to transmit large amount of data without the hidden node problem [11]. Since the vehicles that heard the

RTS or CTS packet must refrain from transmission until the four-way RTS/CTS/data/ACK handshake ends, the exposed node problem is fatal in highly dynamic VANETs.

According to the current IEEE 1609.4 standard, the service provider broadcasts its WSA message that includes a randomly selected SCH without knowing which SCH is selected by possible hidden or exposed service providers. This limitation can cause them to defer their medium access, which is critical in the IEEE 1609.4 multi-channel environments because all the service providers contend for the channel in the short 50ms SCH interval.

As shown in Figure 10, when service user 2 (SU2) is in transmission range of service user 1 (SU1) that has already broadcast its CTS packet, SU2 sets its network allocation vector (NAV) that specifies the required transmission time that SU2 must defer from accessing the medium. Having heard the RTS packet from service provider 2 (SP2), SU2 consequently cannot send its CTS packet to SP2 until the four-way RTS/CTS/data/ACK handshake between SP1 and SP2 ends. Therefore, SP2 has to waste time and energy by repeating the medium access contention and the transmission of its RTS to SU2.

However, if the SCH in which SP2 and SU2 communicate to each other is different from the SCH in which SP1 and SU1 do, SP2 and SU2 can concurrently communicate without being affected by the RTS/CTS/data/ACK handshake by SP1 and SP2.

Therefore, this thesis proposes a new method that enables the exposed service provider to avoid selecting the same SCH number. If the proposed scheme is applied to the example described above in Figure 10, SP1 and SP2 can avoid selecting the same SCH.

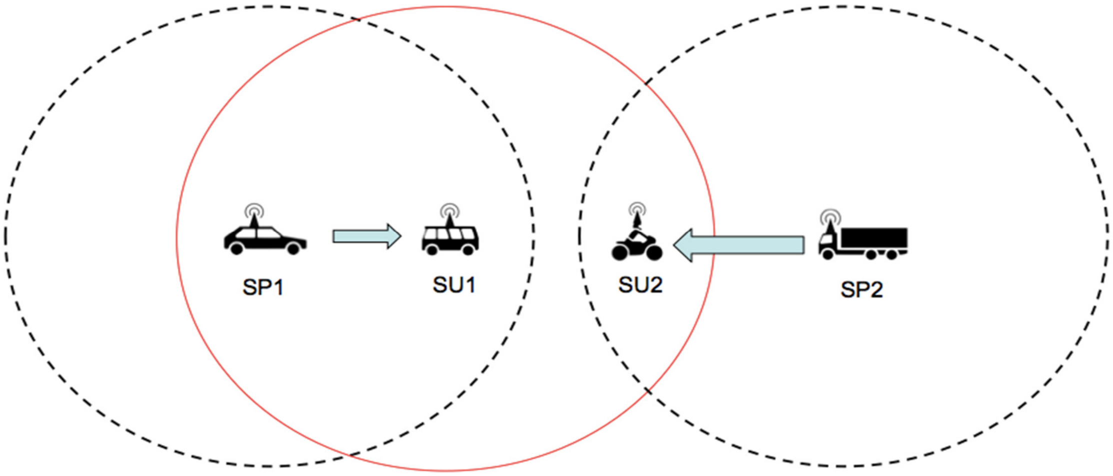


Figure 10. An example of the exposed node problem

Following the definition of the exposed node detailed in [26], SP2 becomes the exposed service provider for the pair SP1 and SU1 in Figure 10. If the exposed service provider can avoid selecting the same SCH number during the CCH interval, the network performance degradation caused by the exposed terminal problem during the SCH intervals will be significantly mitigated in unicast applications under the IEEE 1609.4 multi-channel environment.

4.2.2 Protocol Description

Without modifying the existing standards, our proposed protocol utilizes the unique characteristic of BSM. While mandatory information (e.g., location, speed, direction, and acceleration) are contained in the part I of the BSM, optional information can be included in the part II of the BSM [3]. Our novel protocol piggybacks a candidate SCH selection information into the optional part II of the BSM before broadcasting WSA message. The candidate SCH can be one of the six SCHs (172, 174, 176, 180, 182, or 184) in Figure 1. In this protocol, two terms are defined as follows:

- BSM_SPu: the BSM into which a service provider piggybacks its candidate SCH number with the service user's MAC address in the optional field. It is sent for unicast communication.

- BSM_SU: the BSM into which a service user piggybacks the MAC address of the service provider that first sent the candidate SCH number and the SCH number itself in the optional field.

The roles of a service provider and a service user are specified as follows:

1) Service Provider: By broadcasting its BSM_SPu during the CCH interval, the service provider announces that it intends to communicate with its service user in a particular SCH. Hearing the BSM_SU from its service provider, the service provider can recognize who is the first service provider that sent the particular SCH number. If it is the first, then it wins the SCH and broadcast its WSA message with the finalized SCH number. If it is not the first, it avoids the SCH and follows the Algorithm 1 to determine another SCH to mitigate the exposed node problem.

2) Service User: Since the proposed protocol is on a first come first served basis, the service user has an active role to alert its service provider which service provider first selected the SCH number.

If its service provider is the first, the service user broadcasts its BSM_SU that includes the selected SCH number and the MAC address of the service provider. If the service provider is not the first to select the SCH number, then the service user broadcasts its BSM_SU that includes the same SCH number and the MAC address of the other service provider that first sent the SCH number.

To prevent the service provider that lost competition over the SCH from losing the second SCH again, the service user includes any SCH number(s) that it has heard, if any, when sending the BSM_SU.

The purpose of the MAC address in the BSM_SU is to broadcast which service provider first sent the SCH number. Hearing the BSM_SU, the service provider and any prospective service providers should avoid selecting the same SCH in the BSM_SU.

Before broadcasting the BSM_SPu, a service provider could hear its neighboring vehicles' BSM_SPu or WSA messages. Thus it can recognize which SCHs have already been selected by the neighboring service providers.

According to our proposed scheme, the service provider should select a SCH number that has not been occupied by its neighboring service providers. If all SCHs have already been occupied, the service provider should select the least congested SCH number of the six SCHs. In case the least number ends in a tie (e.g., SCH 172 is selected by two service providers, and SCH 184 is selected by also two service providers), then the service provider randomly selects either SCH 172 or SCH 184.

After a service provider broadcasts its BSM_SPu that includes a candidate SCH number, it follows the Algorithm 2 to determine which SCH number will be finally included in the WSA message.

If the channel is sensed to be idle, the service provider broadcasts its BSM_SPu that includes a candidate SCH number and its service user's MAC address. If the service user receives the BSM_SPu, it broadcasts its BSM_SU in SIFS no matter whether it had already broadcast its regular BSM. However, since the BSM_SPu already includes all the mandatory information in the Part I of the BSM, the service provider does not have to broadcast its regular BSM again.

Algorithm 2 Procedure in selecting SCH number

// Executed by a service provider during the CCH interval

// SCH_set: {172, 174, 176, 180, 182, 184}.
// WSA_sch_num: SCH number in WSA
// SCH_curr: current available SCH number in BSM_SPu
// SCH_next: updated SCH number in next BSM_SPu
// SCH_bsm_su: SCH number in BSM_SU
//SCH_ocpd: SCH numbers SP heard before sending BSM_SPu

//Initialized :
WSA_sch_num = NULL
***if** SCH_bsm_su = SCH_curr*
***then** WSA_sch_num = SCH_curr*
    Return
end if
SCH_curr = a random(SCH_set- SCH_curr -{SCH_ocpd})
WSA_sch_num = SCH_curr
Return

If the service provider does not hear back the BSM_SU from its service user, then it retransmits its BSM_SPu. While the service provider contends for the medium access, the BSM_SPu can be updated. That is, mandatory information in the Part I such as location, speed, direction, or other information can be updated. Besides, the selected SCH can also be changed if the service provider hears the same SCH selection in the other BSM_SPu before it is able to access the medium.

Hearing the BSM_SPu, a service user broadcasts its BSM_SU that is determined by the Algorithm 3.

Algorithm 3 Procedure in selecting SCH number

// Executed by a service user during the CCH interval

// *SP_mac*: Service Provider's MAC address
// *SP_sch*: SCH number selected by Service Provider
// *SU_mac*: Service User's MAC address
// *N_sp_sch*: A count of each SCH that SU heard
// *All_sch*: All SCHs that SU heard
// *BSPu_SUmac*: SU's MAC address in BSM_SPu
// *SM_SU*: SCH number and SP'MAC address in BSM_SU
// *WSP_mac*: MAC address of the other SP won the SCH
// *WSP_sch*: SCH number of the other SP won the SCH
while *BSPu_SUmac* = *SU_mac* **do**
if *N_sp_sch* = 1 **then**
SM_SU = {*SP_mac*, *SP_sch*}
end if*N_sp_sch* > 1
SM_SU = {*WSP_mac*, *WSP_sch*, *All_sch*}
end while
Return *SM_SU*

The information included in the BSM_SU depends on two distinguished situations:

In the case 1, the service user must include the service provider's MAC address and its candidate SCH number in the BSM_SU. Since the BSM_SU includes the service provider's MAC address, it indicates that the service provider first selected the SCH number. Therefore, the service provider can finalize its candidate SCH number into its WSA message and broadcast it. In the case 2, however, the BSM_SU must include the MAC address of the other service provider first selected the SCH number. The service provider loses the SCH because another service provider sent the SCH number earlier that it did.

There are two reasons why the service user immediately broadcasts its BSM_SU in SIFS.

1. To inform its service provider that no other service provider has selected the SCH number. Thus the service provider can win that SCH number.

2. To prevent the service user's neighboring service providers from selecting the same SCH number

4.2.3 Numerical Analysis

If vehicles are distributed as Poisson distribution, the probability of n numbers of vehicles arriving in the network density λ can be modeled using Poisson point process.

$$f(n,\lambda\,) = \frac{\left(\lambda^{n}e^{-\lambda}\right)}{n!} \tag{8}$$

Let *R* be the area where every vehicle in the area becomes a hidden node in relation to a service provider. If *Ř(n)* is the probability of the occurrence that there are *n* numbers of vehicles in the area of *R*, then the probability of arrival of the *n* numbers of vehicles in the area of *R*, which is Λ(*n*) can be expressed as:

$$\Lambda(n) = f(n, \lambda) * \check{R}(n) = \frac{(\lambda^n e^{-\lambda})}{n!} * \check{R}(n) \qquad (9)$$

Suppose that υ is a service provider, and there are *s* numbers of SCHs and n numbers of exposed service users in the area of *R*. *ε(s)* is the probability of the occurrence that all the *n* numbers of exposed service users in the area of *R* tune to different SCHs from the SCH that the vehicle υ selects out of the *s* numbers of SCHs.

$$\varepsilon(n) = \Lambda(n) * \left(\frac{s-1}{s}\right)^n \qquad (9)$$

η(n) is the probability of the occurrence that the vehicle υ selects the same SCH as at least one of the SCHs to which the n numbers of exposed service users tune out of the s numbers of SCHs in the area of *R*.

$$\eta(n) = \Lambda(n) * \left\{1 - \left(\frac{s-1}{s}\right)^n\right\} \qquad (10)$$

If the service provider υ knew a specific SCH is already chosen by other service providers, υ should choose another SCH from the remaining (s–1) numbers of SCHs. η'(n) is the probability of occurrence that the service provider selects the same SCH *again* as at least one of the n numbers of exposed service users in the area of *R*.

$$\eta'(\mathrm{n}) = \Lambda(n) * \left\{1 - \left(\frac{s-1}{s}\right)^{n}\right\} * \left\{1 - \left(\frac{s-2}{s-1}\right)^{n}\right\} \qquad (11)$$

$$\Upsilon(n) = \left\{1 - \left(\frac{s-2}{s-1}\right)^{n}\right\} \qquad (12)$$

η'(n) is always less than η(n) because $\Upsilon(n)$ is greater than zero and less than one in case there are more than one SCH and *n* is greater than zero. Therefore, the exposed node problem can be mitigated by our proposed protocol.

4.3. Performance Verification

The proposed scheme is evaluated and compared to the random SCH selection in this section.

4.3.1 Simulation Setup

The simulations are performed using a Network Simulator (NS-2), which implements the IEEE 1609.4 multi-channel architecture on top of the IEEE 802.11p. Every vehicle operates under the multi-channel DSRC environment depicted in Figure 1. For the real-time mobile scenario, SUMO [25] deployed varying number of vehicles heterogeneously on the roads of Broadway street in San Diego, CA. The major simulation parameters are listed in Table 2, and the results are obtained with 31% confidence interval.

TABLE 2: Simulation Parameters

Parameter	Value
Data Rate	3 *Mbps*
BSM packet size	100 *bytes*
Area	5 km x 5 km
Transmit range	500 m
Number of Vehicles	25-30
Average Speed	45 mph-55 mph
Number of SPs (λ)	2-10
Distribution	Heterogeneous
Mobility	OSM + SUMO
Fading	Nakagami
Simulation Time	100 *seconds*
Confidence Interval	31%

4.3.2 Simulation Results and Analysis

In this sub-section, the following quality metric, average throughput is introduced for the performance comparison of the obtained results. The average throughput is defined as the total useful data that is successfully transmitted per unit time [30].

Firstly, this chapter considered a static scenario where all the vehicles stop due to traffic signal or other reasons. As illustrated in Figure 10, suppose that a service provider 1 (SP1) and its service user 1 (SU1) are in the transmission range of each other. Let the region *R* be the area that is in the transmission range of the SU1 but beyond the transmission range of the SP1. Thus, all the vehicles in the area *R* become the hidden nodes from the service provider. If there is another service user (SU2) in the region *R* and also there is another service provider λ outside of the region R. We performed the simulation by manipulating the number of SU2 in the range R and λ. Both SU2 and λ are uniformly distributed.

Figure 11 shows how the number of λ affects the average throughput. Whether our proposed scheme is applied or not, the average throughput decreases as the number of λ increases. However, as shown in Figure 11, our proposed scheme outperforms the random SCH selection way by average 22%. The performance gain results from the fact that the proposed protocol enables λ to concurrently transmit their packets by avoiding selecting the same SCH number.

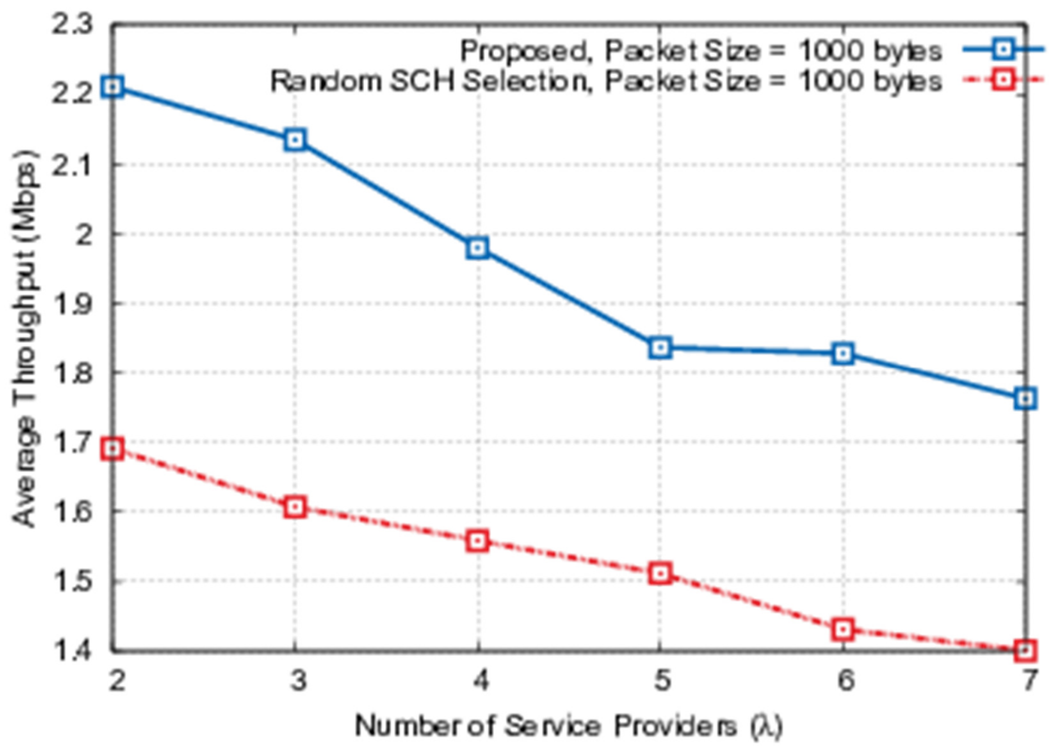


Figure 11: Average Throughput vs Number of service providers (static scenario)

However, the random SCH selection can cause the service provider to select the same SCH as its λ, which delay the time to medium access. Since they are in the same channel, consequently they have to contend for the medium access. The increased time to transmit packet decreases the average throughput. As analyzed, Figure 12 demonstrates that the proposed protocol can substantially decrease the time to access medium compared to the random SCH selection way. As the number of service providers increases, the medium access delay increases. However, the proposed scheme significantly decreases the medium access time when there are less or equal to six SCHs in DSRC spectrum.

Figure 12: Medium Access Delay vs Number of service providers (static scenario)

Secondly, we also considered a moving scenario. For more realistic data, SUMO [25] is used for the trace files of real time traffic of Broadway street, San Diego CA. Vehicles move at 45mph to 55mph.

Figure 13 shows that as λ increases, the average throughput decreases. However, the proposed protocol outperforms the random SCH selection way. The average performance gain is 26%. The mobile scenario's average performance gain is higher than the static scenario's because fast moving vehicles can be already out of the transmission range even during the short time, which deteriorate the average throughput performance. However, our proposed scheme can reduce the medium access delay.

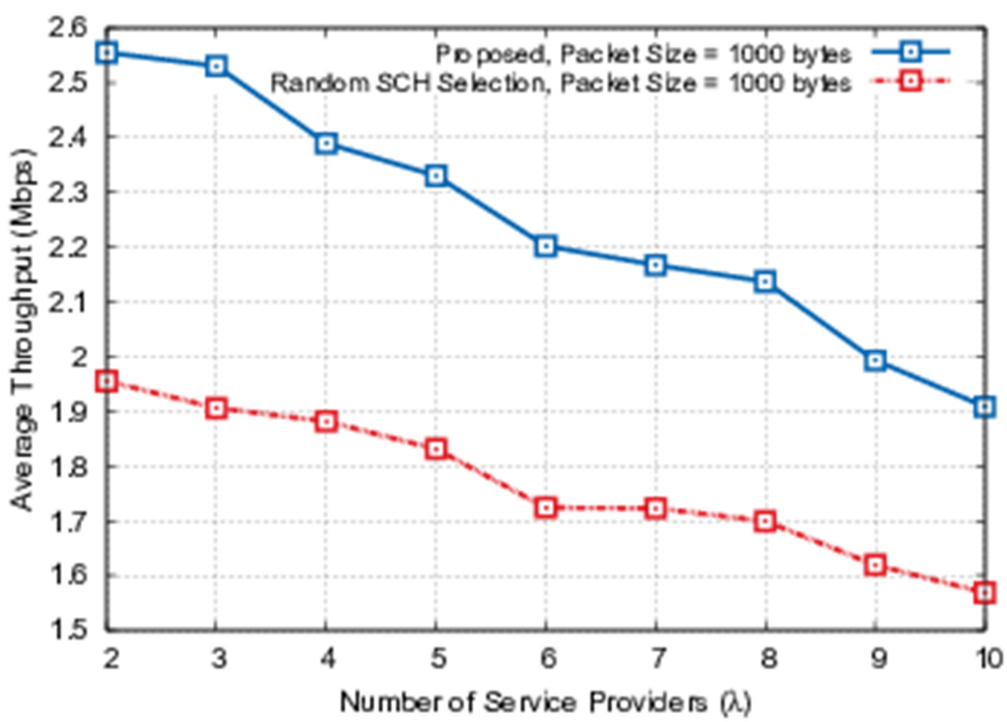


Figure 13: Average Throughput vs Number of service providers (moving scenario)

Figure 14 demonstrates that applying our proposed method can reduce the delay that λ can access the medium. does not defer from accessing medium if it is in different SCH. This proposed method prevents λ from crowding in a particular SCH, which eventually mitigates the channel contention. However, the random SCH selection way does not mitigate the channel contention, and consequently it delays the medium access.

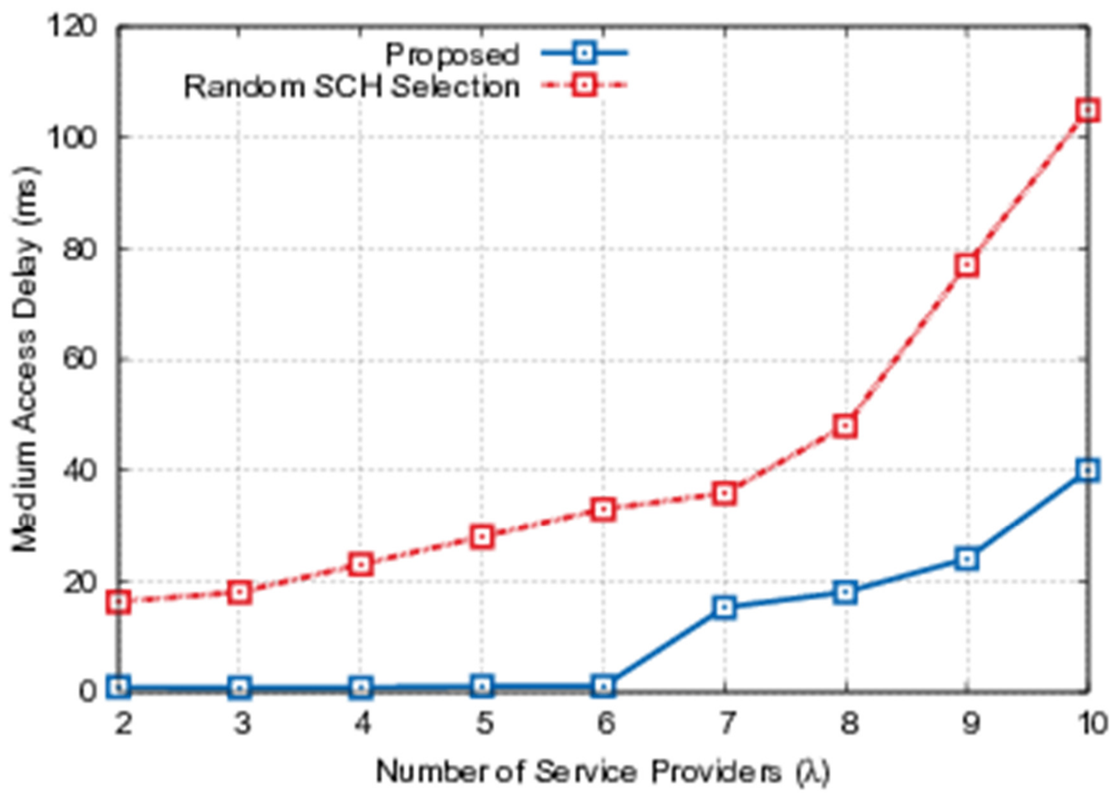


Figure 14: Medium Access Delay vs Number of service providers (moving scenario)

4.4. Conclusions

The proposed protocol enabled a service provider to transmit in parallel while performing the RTS/CTS handshake during the SCH interval. By piggybacking the candidate SCH number in the optional field of the BSM defined by the SAE J2735 standard, a service provider can determine the final SCH number that does not overlap with its exposed node's one. As a result, the service provider can avoid selecting the same SCH, and thus they do not need to defer their medium access in the same SCH, leading to concurrent transmissions. Through extensive simulations, it is verified that this proposed method reduced the medium access delay and improved the average throughput performance by up to 26% compared to the random SCH selection in the IEEE 1609.4 multi-channel unicast scenarios.

CHAPTER V

SINR-based Directional MAC protocol in IEEE 1609.4 VANETs

The Chapter 4 presented the efficient distributed service channel selection method for unicast transmission in the omnidirectional antennas environments. This Chapter further develops the service channel selection scheme for unicast transmission in the directional antennas environments [31].

The main goal of this chapter is to design a novel directional MAC protocol that can increase the overall SINR by maximizing spatial reuse and reducing interference in the IEEE 1609.4 multichannel environment. Since the WSA message of the current IEEE 1609.4 standard does not include direction information, selecting the least congested SCH number does not guarantee the best performance. Moreover, most existing MAC protocols for directional antennas assume ideal directional antennas with the negligible side lobe gain power, which is unrealistic.

To the best of the knowledge, there is a lack of previous work that attempted to solve this unique problem in the IEEE 1609.4 multichannel environment. This Chapter developed the foundation of DMAC [33] and proposed a novel SINR-based Directional MAC (SDMAC) protocol for the IEEE 1609.4 multi-channel vehicular ad-hoc networks. Through theoretical analysis and extensive simulations, the SDMAC incorporated with the multichannel is verified to significantly improve the overall average SINR of the vehicles equipped with realistic directional antennas that have even considerable side lobe gain power.

5.1. Introduction

The FCC allocated an exclusive spectrum called DSRC in the band of 5.9 GHz only for vehicular communications. The DSRC bandwidth consists of one control channel and six service channels where vehicles can transmit safety and control messages during the control channel and infotainment messages during the service channel. The control channel restricts the packets overhead size of the safety and control messages up to 20 bytes and does not allow IP packets. However, the service channel can support the infotainment messages by the *Internet Protocol version 6* (*IPv6*). Therefore, a large amount of data such as multimedia can be transmitted on the service channel, which enables vehicles to upload and download audio or video data on the roads.

If the large amount of data is transmitted to one destination from one source, it is waste of energy to radiate signal toward all the directions using omnidirectional antennas. However, if directional antennas are utilized, a service provider can narrow down the beamwidth of the directional antenna and focus on its target vehicle. This can significantly prevent unnecessary interference to other vehicles. Therefore, the service provider can send data to its service user with higher data rate.

Currently in the IEEE 1609.4 multichannel environment, a service provider broadcasts its WSA message during a CCH interval to inform its service users what SCH to tune in the following SCH interval. However, the WSA message does not includes directivity information because the IEEE 802.11p/1609.4 MAC protocol is designed for omnidirectional antennas. Consequently, the MAC protocols designed for omnidirectional antenna cannot be applied to vehicles with directional antennas despite of the fact that the directional transmission can improve the spatial reuse and wireless network capacity.

If all the vehicles use the omnidirectional antennas, a prospective service provider T can select the least congested SCH number in order to contend with the minimum number of other service providers and minimize the interference among other service providers. However, selecting the least congested SCH number does not always guarantee the minimum interference if the directional antennas are utilized. Whether a service provider interferes another service provider or not depends on beamforming directions of the two service providers if they contend for the same service channel.

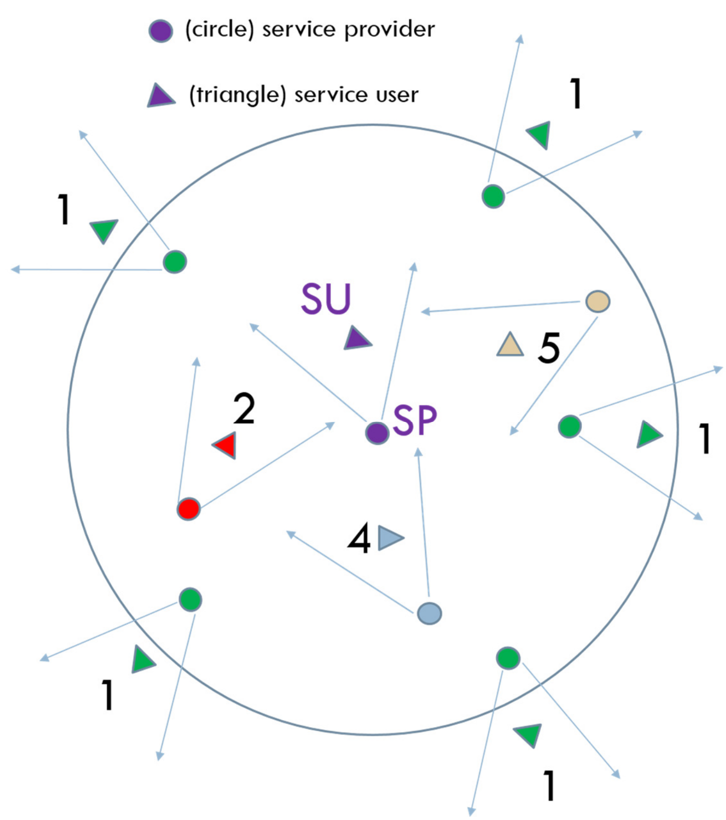


Figure 15: Example topology of directional antenna in IEEE 1609.4 multichannel

As shown in Figure 15, suppose that a prospective service provider is on the center of the circle, which is its transmission range. Let the circle and the triangle be service provider and service user, respectively. Supposed that the number indicates the SCH number that a corresponding service provider selected. The beamforming direction of the service providers is toward their service users. In that example scenario, even though the service provider is informed that the majority of the SCHs that its neighbor service providers have selected is SCH number 1, the SCH number does not interfere the service provider because of their directions. On the contrary, the SCH number 2, 4, and 5 can interfere the service provider because the directions of their directional antennas are toward the service provider despite of the fact that the number of the SCH 2, 4, and 5 is less than the number of the SCH 1. Therefore, selecting the least congested SCH is not the solution to reduce interference in the directional antenna environments.

To the best of the knowledge, few research attempted to solve the directivity coordination problem in the IEEE 1609.4 multi-channel environment. Moreover, most existing directional MAC protocols depend on the model of an ideal directional antenna that assumes the side lobe gain power to be zero, which is not realistic. Consequently, their protocols cannot guarantee the expected performance in practice.

Therefore, the proposed solution considers the realistic directional antennas with non-negligible side lobe gain power as shown in Figure 16. Since the existing directional MAC protocol such as DMAC neglects the side lobe gain power, nodes only consider direction in order not to interfere other nodes. However, if the side lobe power of the directional antenna is considered, the location needs to be considered of the nodes can interfere other nodes. Thus, this proposed method calculates the interference among the nodes under side lobe gain of realistic directional antennas to obtain signal-to-interference-plus-noise ratio (SINR) values. The directional antenna environment necessities the angle information between two nodes to compute the SINR value. According to this proposed scheme, the beamforming direction information of the directional antenna is piggybacked into the BSM so that service providers can obtain both SCH number and direction information.

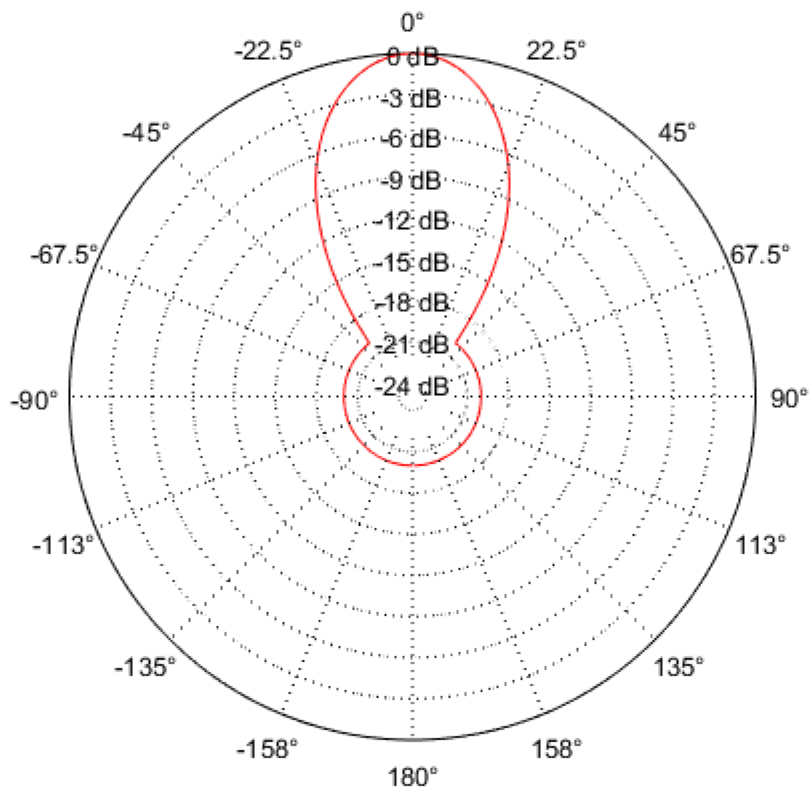


Figure 16: The directional antenna gain pattern

In accordance with the proposed directional MAC protocol, a prospective service provider *T* calculates its neighbor service provider/user pairs and classifies them according to their SINR values. The service provider/user pair that has the lower SINR value than threshold SINR, the pair is categorized as interfering pair (*I*-pair). The service provider *T* counts how many *I*-pairs are biased to each of six SCHs. Then the service provider *T* select the SCH number that has the least number of I-pairs. If the number of I-pairs are tied at multiple SCHs, the maximizing sum rate optimization algorithm is performed.

The proposed solution is compared with other possible approaches: the least congested selection and random selection. Theoretical analysis and extensive simulation results demonstrate that this proposed method outperforms the least congested selection and random selection. As a result, the proposed directional MAC protocol can improve the wireless network capacity by maximizing the spatial reuse and minimizing the interference.

5.2. Protocol and Algorithm for Directional Antennas

5.2.1 Motivation

Using omnidirectional antennas for unicast communications reduces the spatial reuse and the channel utilization by unnecessarily radiating energy toward all the directions. However, directional antenna can focus on a target vehicle and increase the spatial reuse and concurrence transmissions compared to omnidirectional antenna. This chapter attempts to address how the directional antenna can be applied to the IEEE 1609.4 multi-channel environments. As explained in the previous chapter, the current IEEE 1609.4 standard does not specify what SCH number a service provider should select. Consequently, the service provider selects a SCH number randomly unless any SCH selection rule is specified, which can limit the potential of directional antennas. In the existing standard, having heard WSAs from its neighbor service providers during the CCH interval, the service provider T only has the information of the SCH number. Therefore, the service provider T is not able to know what directions its neighbor service providers will transmit in the following SCH interval. In addition, the service provider T does not know the beamwidth of the directional antenna and the locations of the service users of its neighbor service providers. With this limited information, the service provider T cannot exploit the advantage of using directional antenna.

Selecting a SCH number that neighbor service providers have not select could be a simple rule. As shown in Figure 17, for example, if a service provider T hears WSA messages broadcast by service providers, A, B, and C, then the service provider T should avoid the SCH numbers (eg., 2,4,5) and randomly select a SCH number out of the remaining SCH numbers (eg., 1,3,6). In that case, the four service providers can concurrently transmit data to their service users.

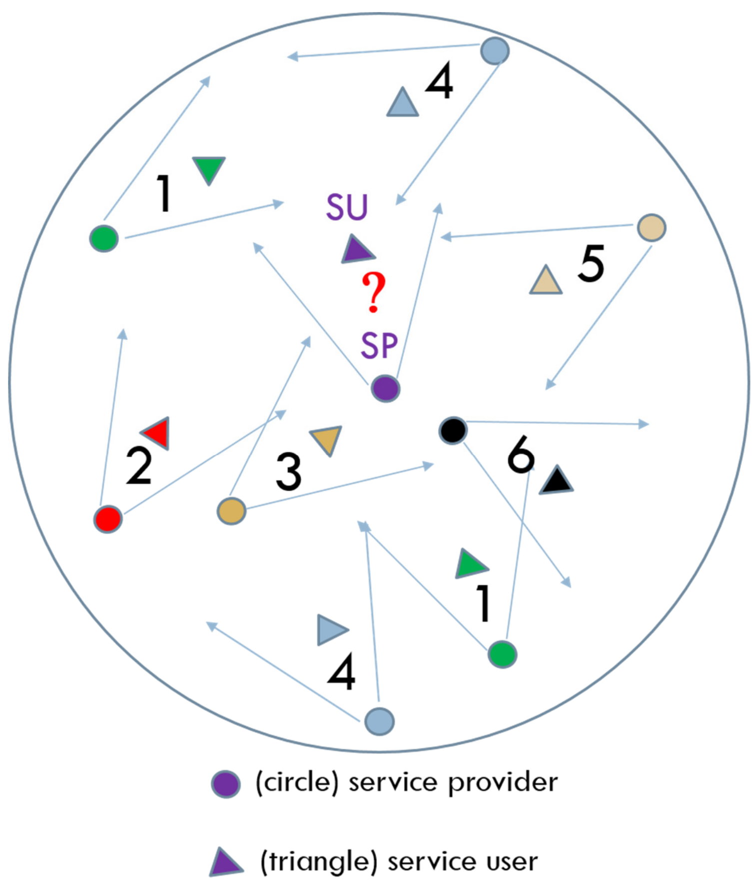


Figure 17: SCH number selection for directional antenna

However, as shown in Figure 17, if there are more than five service providers that have occupied all the available SCHs, then what SCH number should the service provider *T* select? The service provider *T* must select the SCH number that contributes to increase concurrent transmission by all the service providers.

Moreover, the best choice of the SCH number also varies with the location of the service user *R*. The least congested SCH number would not always the best SCH selection. Selecting the least congested SCH number could be suggested. However, unlike the omnidirectional antennas, selecting the least congested SCH number does not always guarantee the best solution. Suppose that the service provider *T* heard that two service providers selected the SCH number 2, and three service providers selected the SCH number 3. In omnidirectional antenna environments, the service provider *T* would select the SCH number 2 over the SCH number 3. However, as the example shown in Figure 15, selecting the SCH 2 over the SCH number 3 does not always guarantee the better network performance.

In the IEEE 1609.4 standard, if vehicles once enter a SCH interval, they are not allowed to change their SCH until the end of the SCH interval. In other words, since vehicles can tune to only one SCH frequency during each of the SCH interval, directional MAC protocol for single channel is required during each of the SCH interval. First, I will apply an existing directional MAC protocol to the IEEE 1609.4 environment and address its limitation in realistic directional antenna. Finally, I will design a novel directional MAC protocol for more realistic directional antenna.

5.2.2 Protocol Description

The proposed SINR-based Directional MAC (SDMAC) protocol considered the side lobe gain power of directional antennas and developed the foundation of the DMAC to adapt to the realistic directional antennas in the IEEE 1609.4 multichannel environment.

During the CCH interval, a service provider broadcasts its *BSM_SP_D* to inform its *candidate* SCH number before the service provider finalizes its SCH number in its WSA message. If the service provider has not heard any *BSM_SP_D* from its neighbor vehicles, the service provider can randomly select one of the six SCH numbers. If the service provider has heard several *BSM_SP_Ds* or WSAs that include their SCH numbers, the service provider should avoid the selected SCH numbers and randomly select one of the remaining SCH numbers. However, if all the SCH numbers have already been occupied by neighbor service providers, the service provider follows either the Algorithm 4 or Algorithm 5 depending on the directional antenna. If the gain power of the side lobes of the directional antenna is negligible, the service provider follows the Algorithm 4. However, if the gain power of the side lobes of the directional antenna is realistically significant, the service provider must follow the Algorithm 5.

DMAC protocol

The DMAC protocol is a MAC protocol that is designed for directional antenna. Basically, the DMAC modified the characteristics of the IEEE 802.11 such as the RTS/CTS/data/ACK handshake and NAV under CSMA/CA to adapt to directional antenna systems [33]. According to the DMAC, the channel is reserved by directionally transmitted

RTS/CTS. However, idle nodes listen to the channel in omnidirectional mode because they are not able to know what direction a signal arrives from.

According to the DMAC, the directional network allocation table (DNAV) maintains the information of directions toward which a node must defer transmission [33]. When the existing DMAC is adopted for MAC protocol to the WAVE environment, a service provider must check the DNAV table and find the direction information to avoid interfering its neighbor service provider. Having heard the *BSM_SP_Ds*, the service provider is able to recognize whether it is in the directional transmission range of its neighbor service providers because the *BSM_SP_D*s from its neighbor service providers include not only its neighbor service providers' beamwidth and radius but also the service users' location information. Specifically, if the angle between the service provider and its neighbor service provider is less than threshold angle θ_{th}, the service provider should avoid selecting the same SCH number as its neighbor service provider already selected. It is assumed that all vehicles have a beamwidth of angle β. Let ε be the angular separation between the edges of beamforms, then the threshold angle θ_{th} is expressed as following:

$$\theta_{th} = \beta + \varepsilon \tag{13}$$

Having heard *BSM_SP_D*, the service provider selects its candidate SCH number according to the Algorithm 4.

Since DMAC assumes the gain power of the side lobes to be very low, all the vehicles that hear the directional RTS defer their transmission only towards the service provider that sent the directional RTS.

Algorithm 4 Procedure in selecting SCH number

```
// Executed by a service provider during the CCH interval

  // SCH_set: {172, 174, 176, 180, 182, 184}.
  // SCH_curr: current available SCH number in BSM_SP_D
  //SCH_ocpd: SCH number SP heard before sending BSM_SP_D
  // SP: service provider
  // SU: service user
  // θ : the angle between SP and SU
  // θ_th: threshold angle
  // NBSP: neighbor service provider
  // DTR: directional transmission range

  SCH_curr = NULL

  while SP in DTR of NBSP
        if θ < θ_th
                then SCH_curr  = a random(SCH_set - SCH_ocpd)
        else
                then SCH_curr  = SCH_ocpd
        Return
        end if
  end while
```

However, even though the vehicles that heard the RTS from the service provider avoid transmitting towards the service provider, the vehicles in the service user's vicinity can interfere the service user if they transmit toward the service user. Likewise, all the vehicles that hear the directional CTS from the servicer user can interfere the service provider even though they defer their transmission only towards the service use that sent the directional CTS.

However, in the realistic directional antennas, the gain power of the side lobes is not too negligible to ignore. The more significant the gain power of the side lobes, the more vulnerable to the interference the service user is. Therefore, this gain power issue of the realistic directional antennas must be considered to design a novel MAC protocol. I designed an SINR-based directional MAC (SDMAC) protocol. The main contribution of the SDMAC is to consider the gain power of the side lobes.

In this SDMAC protocol, two terms are defined as follows:

- *BSM_SP_D*: the BSM into which a service provider piggybacks its *candidate* SCH number, its service user's ID, the beamwidth, transmit power

- *BMS_SU_D*: the BSM into which a service user piggybacks the *candidate* SCH number that its service provider selected, its service provider's ID, the beamwidth, transmit power

According to this SDMAC protocol, all the service providers must broadcast their *BSM_SP_D* before sending their WSAs until the end of the CCH interval. Suppose that a service provider *T* intends to transmit data to its service user R during the SCH interval. The information collected from the *BSM_SP_D*s can determine what SCH number the service provider *T* should choose. If the service provider T has not heard any *BSM_SP_D*, then it can select any SCH number and piggyback it into its *BSM_SP_D.* If the service provider *T* have heard *BSM_SP_D*s, it should avoid selecting the same SCH number. However, suppose that the *BSM_SP_D*s that the service provider *T* have heard occupy all the available SCH numbers. As explained in the chapter 5.3.1, selecting the least congested

SCH number in directional antenna environment does not guarantee the best performance.

In that case, the service provider *T* follows the Algorithm 5.

Algorithm 5 Procedure in selecting SCH number

```
Initialize
Event check to see if selection of a channel meets SINR constraint
        sinr_constraint = false(1,num_channel);
for kdx = 1:num_channel
        sinr_constraint(kdx)
         = all( tmp_sinr_vec(tmp_sinr_vec(:,kdx) > 0,kdx) >= SINRmin );
end
Event Get Selected Channel Index
        channel_index = 1:num_channel;
switch opttype
case 'random'
        if any( sinr_constraint )
                cand_chan = channel_index( sinr_constraint );
                rp_idx = chanrand.randi( [1,length(cand_chan)], 1, 1 );
                select_chan_index = cand_chan( rp_idx );
        else
                select_chan_index = [];
        end
case 'least congested'
// Min Cardinality
        chan_cardinality = zeros(1,num_channel);
        for kdx = 1:num_channel
                chan_cardinality(kdx) = sum(node_channel == kdx);
        end
        cardinal = zeros(1,num_channel);
        for kdx = 1:num_channel
                if sinr_constraint(kdx) == false
                        cardinal(kdx) = 100*num_node;
                else
                cardinal(kdx) = chan_cardinality(kdx);
        end
        end
        if min( cardinal ) <= (2*num_node)
                cand_chan = channel_index( min( cardinal ) == cardinal );
                rp_idx = chanrand.randi( [1,length(cand_chan)], 1, 1 );
                select_chan_index = cand_chan( rp_idx );
        else
                select_chan_index = [];
```

```
        end
case 'max-sumrate'
        // Min Cardinality
        chan_cardinality = zeros(1,num_channel);
        for kdx = 1:num_channel
                chan_cardinality(kdx) = sum(node_channel == kdx);
        end
// Max Sumrate
        sumrate_vec = zeros(num_channel,num_channel);
        sumrate = zeros(1,num_channel);
        for kdx = 1:num_channel
                if sinr_constraint(kdx) == false
                        sumrate(kdx) = -1;
                else
                sumrate_vec(kdx,kdx) = sum( log2( 1 + ( tmp_sinr_vec(tmp_sinr_vec(:,kdx)
                > 0,kdx) ) ) );
                for jdx = 1:num_channel
                        if kdx ~= jdx
                        sumrate_vec(kdx,jdx) = sum( log2( 1 + ( sinr_vec(sinr_vec > 0) ) ) );
                        end
                end
                sumrate(kdx) = sum( sumrate_vec(kdx,:) );
        end
end
max_sumrate = max( sumrate );
if sumrate > 0
        cand_chan = channel_index( max_sumrate == sumrate );

        card_list = chan_cardinality( cand_chan );
        cand_chan2 = cand_chan( card_list == min(card_list) );

        rp_idx = chanrand.randi( [1,length(cand_chan2)], 1, 1 );
        select_chan_index = cand_chan2( rp_idx );
else
        select_chan_index = [];
end
```

Having heard the *BSM_SP_D*s or WSAs from the neighbor service providers, the service provider *T* has the information of their beamwidth, the location of their service users, and their direction of arrival and departure. Since the service provider *T* knows the location of its neighbor service provider/user pair, it can calculate the Euclidean distance between its neighbor service provider and user pair. In addition, the service provider *T* can also calculate how it interferes its neighbor service provider/user pair. Likewise, the service provider can calculate how its service user *R* interferes the same service provider/user pair. From the perspective of the service provider/user pair, all transmissions from the service provider *T* and the service user *R* act as interference. Therefore, the service provider *T* can calculate the SINR value of its neighbor service provider/user pair. Since the service provider *T* knows the location of its service user *R*, the service provider *T* can calculate how the service user *R* can interfere the neighbor service provider/user pair. That is, the service provider *T* is able to obtain the received signal power of the neighbor service provider/user pair and the interference power from the service provider *T* and the service user *R*.

Therefore, the service provider *T* can determine that its transmission to its service user R, which acts as interference to its neighbor service provider/user pair can lower their SINR values below a given threshold SINR value. If the SINR value is below the given threshold SINR, the service provider *T* or the service user *R* can cause the transmission between the neighbor service provider/user pair to fail to be decoded. Having heard the BSM_SP_Ds, the service provider *T* can recognize the SINR values of all the neighbor service provider/user pairs. Therefore, if the service provider lowers the SINR value of the neighbor service provider/pair below the threshold SINR, the service provider should avoid selecting the SCH number that the neighbor service provider selected.

However, there could be more than six neighbor service provider/user pairs that occupied all the available six SCH numbers. In that case, the service provider *T* calculates the SINR values of all the neighbor service provider/user pairs and classifies them into two groups. The neighbor service provider/user pairs that have higher SINR value than the threshold SINR is classified to the first group, and the neighbor service provider/user pairs that have lower SINR value than the threshold SINR are classified to the second group. The service provider *T* ranks the six SCH numbers in order of what SCH number has the least numbers of the service provider/user pairs that have lower SINR value than the threshold SINR. Finally, the service provider *T* should select the highest ranked SCH number.

In the case of that there are more than one SCH that have the same number of the service provider/user pairs, the service provider T performs the optimization algorithm to increase the wireless network system performance. There are two optimization algorithm: the sum rate maximization and the minimum SINR maximization. The former is that the service provider *T* selects the SCH in which the sum of the throughput of all the service provider/user pairs is the greatest. The latter is that the service provider *T* selects the SCH in which the minimum SINR value of all the service provider/user pairs is the greatest. The more details will be explained in detail in the Chapter 5.3.3.*B*.

5.2.3 Theoretical Analysis

5.2.3.1 Threshold SINR

The minimum threshold SINR value that is required to communicate can be calculated by the Shannon-Hartley theorem:

$$C = \mathrm{B}\, log_2(1 + SINR) \tag{14}$$

The term B is the bandwidth of the channel in *Hz*, which is 10 MHz in the IEEE 802.11p/1609.4 WAVE standard. The term *C* is the channel capacity in bits per second. The IEEE 802.11p provides data rates, 3, 6, 9, 12, 18, 24, 27 Mbps.

The term *N* is the Additive white Gaussian noise (AWGN) power, which can be calculated from the noise spectral density, -174dBm/Hz. Since the bandwidth is 10 MHz, noise power *N* at 10 MHz bandwidth is calculated as:

$$N = -174\ dBm + 10log_{10}(10^6)\ dBm \tag{15}$$

$$= -174\ dBm + 60\ dBm$$

$$= -114\ dBm$$

If data rate is set to 3 Mbps, which is the minimum data rate, the minimum SINR value can be calculated from the Shannon-Hartley theorem as:

$$10 * 10^6\ log_2(1 + SINR) = 3 * 10^6 \tag{16}$$

$$SINR = 2^{\frac{3}{10}} - 1$$

Since the minimum SINR value is $2^{\frac{3}{10}} - 1$, if received signal power S is known, the maximum interference I can be calculated as:

$$\frac{S}{I + N} = 2^{\frac{3}{10}} - 1 \tag{17}$$

$$I = \frac{S}{2^{\frac{3}{10}} - 1} - N \tag{18}$$

The SINR outage is calculated in *dB* scale as:

$$10 * log_{10}\left(2^{\frac{3}{10}} - 1\right) = -6.36\ [\text{dB}]$$

If a service provider *T* hears *BSM_SP_D*s from neighbor service providers, the service provider *T* can recognize what SCH numbers had been selected by its neighbor service providers. In addition to the SCH numbers, having heard the *BSM_SP_D*s, the service provider *T* can obtain the information of the location, the beamwidth, the transmission power, the radius of the beam, and the distance of its neighbor service providers and service users. From the information, the service provider *T* can calculate the SINR values of its neighbor service users. If the SINR value of a service user is lower than the minimum threshold SINR value, the service provider *T* should avoid using the same SCH number as its service user/provider pair already selected.

5.2.3.2 Minimizing cardinality subject to SINR constraints: the sum rate maximization and the minimum SINR maximization

Let Ψ be a SCH number set {172, 174, 176, 180, 182, 184}, and Φ be a subset of Ψ, which includes the least number of the service provider/user pairs that have the lower SINR value than the threshold SINR. Since there are only six available SCHs in the DSRC spectrum, the least number of the service provider/user pairs that have the lower SINR value than the threshold SINR can be tied at multiple SCHs. For example, suppose that two SCHs (e.g., SCH 172 and SCH 184) have the same number of the service provider/user pairs that have the lower SINR value than the threshold SINR. Suppose that each of the SCHs has two service provider/user pairs. For example, a service provider/user pair 1 and another service provider/user pair 2 is in the SCH 172, and a service provider/user pair 3 and another service provider/user pair 4 is in the SCH 184. In that environment, a service provider *T* is required to select one of the two SCHs before transmitting its service user *R*.

There are two cases:

1) The case that service provider *T* selects the SCH 172:
   - In SCH 172, The SINR values of the service user 1, 2, and *R* can be {α, β, γ}
   - In SCH 184, The SINR values of the service user 3 and 4 can be {δ, ε}
2) The case that service provider *T* selects the SCH 184:
   - In SCH 172, The SINR values of the service user 1 and 2 can be {a, b}
   - In SCH 184, The SINR values of the service user 3, 4, and *R* can be {c, d, e}

In the above two cases, the service provider T needs to determine what SCH number it should select to improve the network system performance according to the SINR values. Since there are multiple numbers of SINR values, the service provider T should compare the two vectors $\vec{A}$ and $\vec{B}$ that indicate the multiple SINR values as follows:

$$\vec{A} = \begin{bmatrix} \alpha \\ \beta \\ \gamma \\ \delta \\ \varepsilon \end{bmatrix} \qquad \vec{B} = \begin{bmatrix} a \\ b \\ c \\ d \\ e \end{bmatrix}$$

where the vector $\vec{A}$ represents the SINR values of the service users in the SCH 172, and the vector $\vec{B}$ represents the SINR values of the service users in the SCH 184. Since it is difficult to directly compare the vector $\vec{A}$ with the vector $\vec{B}$, the sum rate maximization optimization is performed to compare the vector $\vec{A}$ with the vector $\vec{B}$. Since throughput is proportional to $log_2(1 + SINR)$, the SINR vector can be transformed to one value for comparison. The sum rate of the SINR vector is defined as:

(19)

$$\sum_{i=1}^{n} log_2(1 + \frac{10^{SINR_i}}{10})$$

Let the sum rate of the vector $\vec{A}$ be $\Sigma(\vec{A})$ and the sum rate of the vector $\vec{B}$ be $\Sigma(\vec{B})$. $\Sigma(\vec{A})$ and $\Sigma(\vec{B})$ can be expressed as follows:

$$\Sigma(\vec{A}) = log_2(1 + \frac{10^{\alpha}}{10}) + log_2(1 + \frac{10^{\beta}}{10}) + log_2(1 + \frac{10^{\gamma}}{10}) + log_2(1 + \frac{10^{\delta}}{10}) + log_2(1 + \frac{10^{\varepsilon}}{10})$$

$$\Sigma(\vec{B}) = log_2(1 + \frac{10^{a}}{10}) + log_2(1 + \frac{10^{b}}{10}) + log_2(1 + \frac{10^{c}}{10}) + log_2(1 + \frac{10^{d}}{10}) + log_2(1 + \frac{10^{e}}{10})$$

If $\Sigma(\vec{A})$ is greater than $\Sigma(\vec{B})$, then the service provider *T* should select the SCH 172. However, if $\Sigma(\vec{B})$ is greater than $\Sigma(\vec{A})$, then the service provider *T* should select the SCH 184.

According to the minimum SINR maximization, the service provider *T* compares the minimum of vector $\vec{A} = [\ \alpha\ \beta\ \gamma\ \delta\ \varepsilon\ ]$ with the minimum of vector $\vec{B} = [\ a\ b\ c\ d\ e\ ]$. If the minimum of vector $\vec{A} = [\ \alpha\ \beta\ \gamma\ \delta\ \varepsilon\ ]$ is bigger than the minimum of vector $\vec{B} = [\ a\ b\ c\ d\ e\ ]$, the service provider T should select the SCH 172. Otherwise, if the minimum of vector $\vec{B} = [\ a\ b\ c\ d\ e\ ]$ is bigger than the minimum of vector $\vec{A} = [\ \alpha\ \beta\ \gamma\ \delta\ \varepsilon\ ]$, the service provider *T* should select the SCH 184.

5.2.3.3 Directional Antenna model for 5.9 GHz

Suppose that a service provider T transmits with a transmit power P_t, then the received power P_r by a service user R is calculated as

$$P_r = HP_t \tag{20}$$

H is a channel gain between the service provider T and the service user R. According to the standard Friss equation [58]:

$$P_r = \left(\frac{\lambda}{4\pi d}\right)^2 e^{-\alpha d}\, G_t G_r P_t \tag{21}$$

Thus the channel gain H can be expressed as

$$H = \left(\frac{\lambda}{4\pi d}\right)^2 e^{-\alpha d}\, G_t G_r \tag{22}$$

where the wavelength λ is expressed as

$$\lambda = \frac{v}{f_c} \tag{23}$$

where v is the phase speed, and f_c is the carrier frequency, which is 5.9 GHz in the IEEE 802.11p/1609.4 WAVE. The parameter α is the pathloss index indicating the loss by oxygen absorption, which can reach 16 dB/km [55].

$$\alpha = 0.0016 * log_e(10) = 0.0037/m \quad (24)$$

G_t and G_r are the directional antenna gain of the transmitter and the receiver, which represent the antenna directivities, and the parameter d is the Euclidean distance between the transmitter and the receiver.

The received power, P_r can be calculated by the contemporary formula of the Friss equation, which can be modified in dB scale as follow:

$$P_r = P_t + G_t + G_r - pathloss \quad (25)$$

$P_t, G_t,$ and G_r represent the transmit power, transmit gain, and receive gain, respectively. The pathloss can be expressed in dB scale as:

$$pathloss = C + 10n\ log_{10}(d) \quad (26)$$

The term C is a constant for system losses, and n is the pathloss exponent, and d is the Euclidean distance between the transmitter and the receiver. From the results of measurements [57], the model of pathloss, PL is developed as follows.

$$PL = 40log_{10}(d) + 9.45 - 34.6log_{10}(h-1) + 2.7log_{10}(\frac{f_c}{5.0}) \quad (27)$$

The term d is the distance in meter between the transmitter and the receiver, f_c is the carrier frequency in *GHz*, and h is the height of the antenna from the ground in meter.

Finally, the directional antenna gain, G_t and G_r can be calculated as:

$$G(\theta) = -\min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, G_m\right], (-180^o \leq \theta \leq 180^o) \tag{28}$$

θ is azimuthal angle with respect to the direction of the beamforming of the directional antenna. Thus, the boresight direction is at $\theta = 0$. θ_{3dB} is the beamwidth, which is the angular separation between two 3dB drop points. G_m is the minimum gain.

As mentioned previously, having heard the *BSM_SP_D*s, the service provider *T* is informed the location, beamwidth of its neighbor service providers and service users. Therefore, the service provider *T* can calculate the SINR values of its neighbor service users. From the perspective of the service provider *T*'s neighbor service users, the received signal from the service provider *T* is interpreted as an interference. The SINR value of a service user can be calculated if the received signal power from its service provider and the interference from the service provider *T* are known.

The received signal power of a service user R of its service provider T can be expressed as:

$$P_r = P_t + G_t(0) + G_r(0) - PL(\overline{SP - SU}) \tag{29}$$

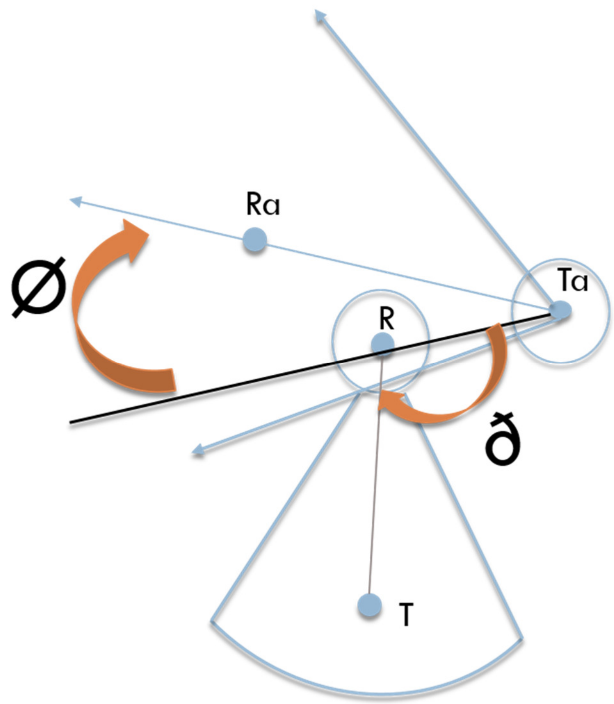


Figure 18: Directional antenna gain

P_t is the transmit power of the service provider *T* and is known because the *BSM_SP_D* includes the value. Pathloss is a function of the distance between the service provider and the service user, which is also known. Since the service provider's directional antenna beamforms to its service user, which means that they are in the boresight direction each other, θ is zero.

The interference power is the signal power from unwanted direction. For example, as shown in Figure 18, the interference power of the service user *R* can be calculated as:

$$I_r = P_t + G_t(\text{Ø}) + G_r(\text{ð}) - PL(\overline{Ta - R}) \tag{30}$$

The interference power I_r is the signal power from unwanted direction. Ø is the angle between $\overline{Ta - R}$ and $\overline{Ta - Ra}$, and applied to the transmit gain in equation (28). ð is the angle between $\overline{R - T}$ and $\overline{R - Ra}$, and applied to the receive gain in equation (28). P_t is the transmit power of the service provider Ta, and the distance between the service provider Ta and the service user *R* is applied to the pathloss in equation (27).

Since the *BSM_SP_D* includes P_t value and the location of the service provider and the service user, the service provider *T* can calculate the PL value, which is a function of the distance between the service provider/user pair. Therefore, the service provider *T* can calculate the received signal power of its neighbor service user.

When the service provider *T* transmits signal to its service user *R*, the signal can be interference from the perspective of the service provider *T*'s neighbor service user. The service provider *T* can calculate the interference power because it knows its transmit power, the angle between its service user *R* and its neighbor service user, the angle between boresight and its neighbor service provider.

5.3 Performance Verification

In this section, the performance of the proposed SINR-based Directional MAC protocol is evaluated against the least congested SCH selection and the random SCH selection in the IEEE 1609.4 multichannel environment. Details for the simulation environment are depicted with the results in the following sections.

5.3.1 Simulation Setup

Vehicles are randomly distributed in a 2-*D* space in a Poisson distribution over the area *A* with a density σ. The vehicle density is defined as one vehicle over $\frac{1}{\sigma^2}m^2$. In other words, there is one vehicle over σ square meter. The major simulation parameters are listed in Table 3.

TABLE 3: Simulation Parameters

Parameter	Value
Transmit Power	23 dBm
Noise Figure	5 dB
Maximum antenna gain	13 dBi
Transmission range	300 *m*
Channel bandwidth	10 *MHz*
Beamwidth	$30^o, 60^o, 90^o, 120^o$
Number of SCHs	6
Fading	Nakagami
Area	2 *km* x 2 *km*
Antenna height	1.5 *m*
Carrier frequency	5.9 *GHz*

5.3.2 Simulation Results and Discussion

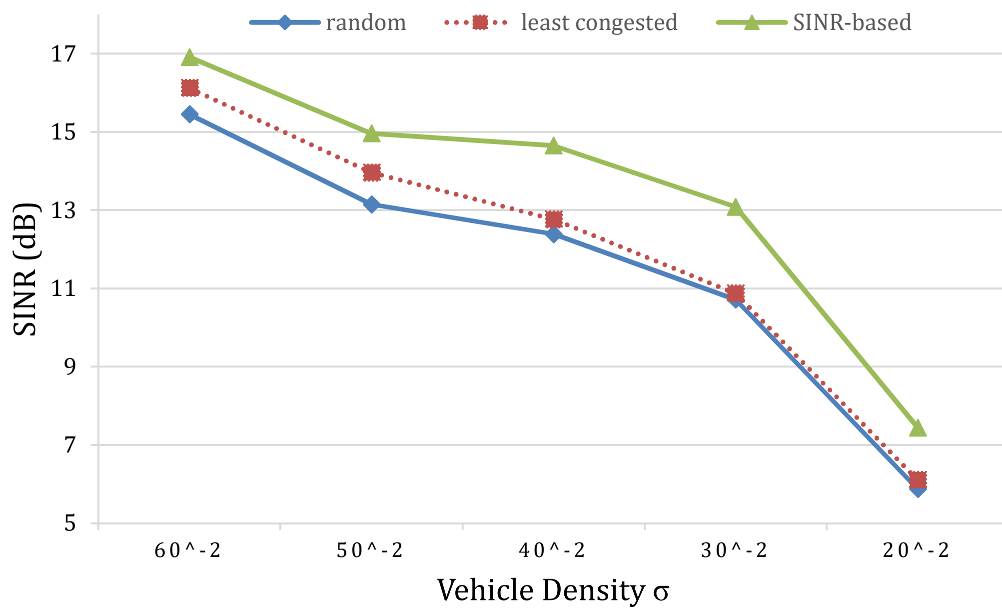
The performance of the proposed SINR-based Directional MAC protocol is evaluated via simulations. The results of the proposed method are compared with the method of the least congested SCH selection and the random SCH selection.

The signal-to-interference-plus-noise ratio (SINR) value will be used for performance metric.

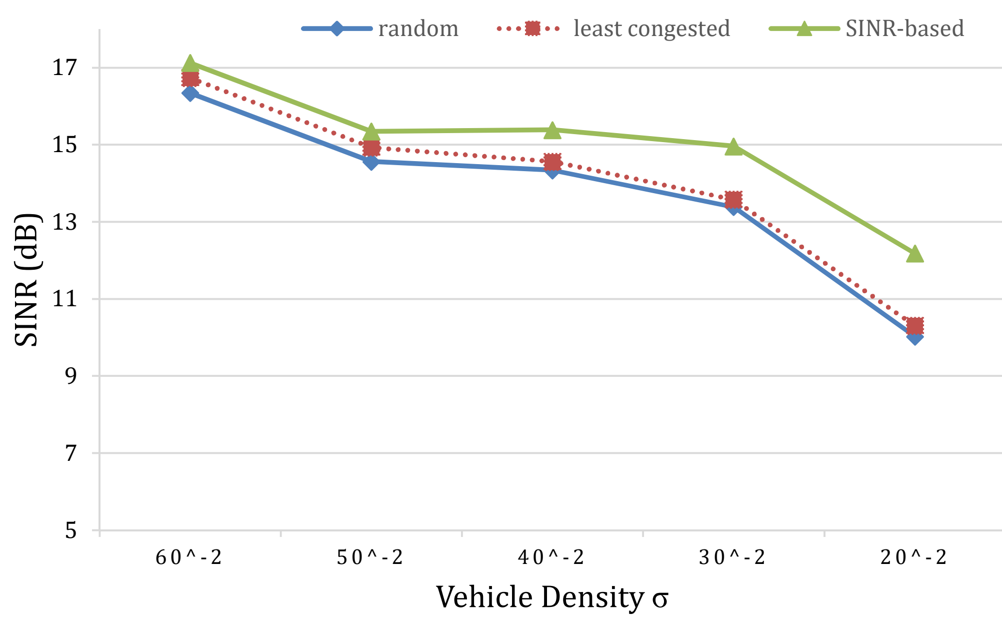
$$SINR = \frac{P}{I + N} \tag{30}$$

From the point of a service user, *P* is the received power of the incoming signal from its service provider. *I* is the interference power of other interfering signals, which come from other service providers. *N* is the background noise power.

First, as shown in Figure 19 (a), it is observed that the average SINR value decreases as the vehicle density increases no matter what method is applied. Out of the three methods, the random SCH selection method performs the worst. The least congested SCH selection method outperforms the random SCH selection method from the density $\sigma = \frac{1}{60^2}$ to the density $\sigma = \frac{1}{20^2}$. As already explained in the Chapter 5.1, the least congested SCH does not always guarantee the best performance because of the directivity of the directional antenna. In spite of that, the average SINR values of the least congested SCH method is slightly higher than the random SCH selection method. The reason is that the least congested SCH selection approach enabled the service provider to avoid several SCHs that can interfere the service provider. Especially, when the vehicle density is lower, the least congested SCH selection scheme achieves higher SINR values because there are relatively less vehicles that can interfere toward the service provider.



(a) Beamwidth: 60°



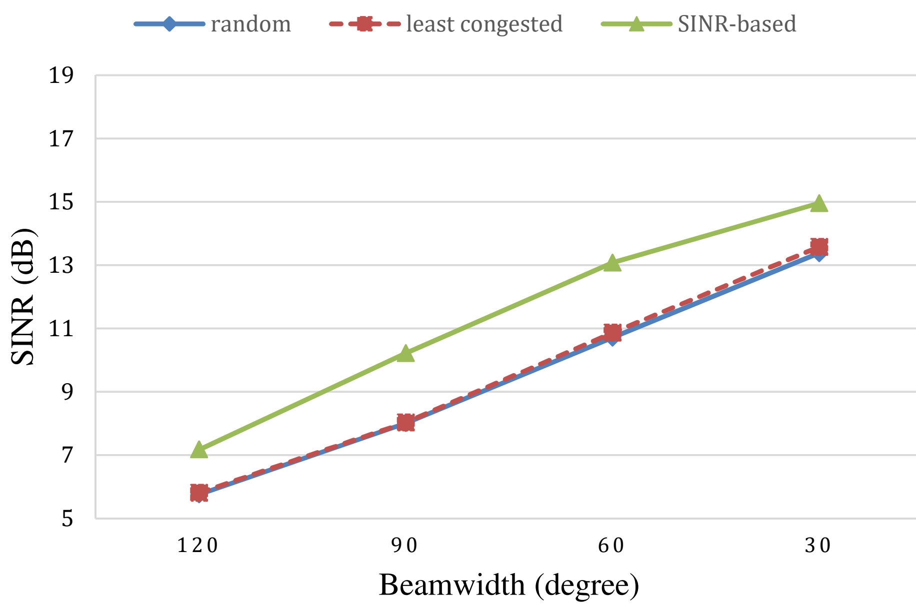
(b) Beamwidth: 30°

Figure 19: Average SINR of vehicles vs vehicle density

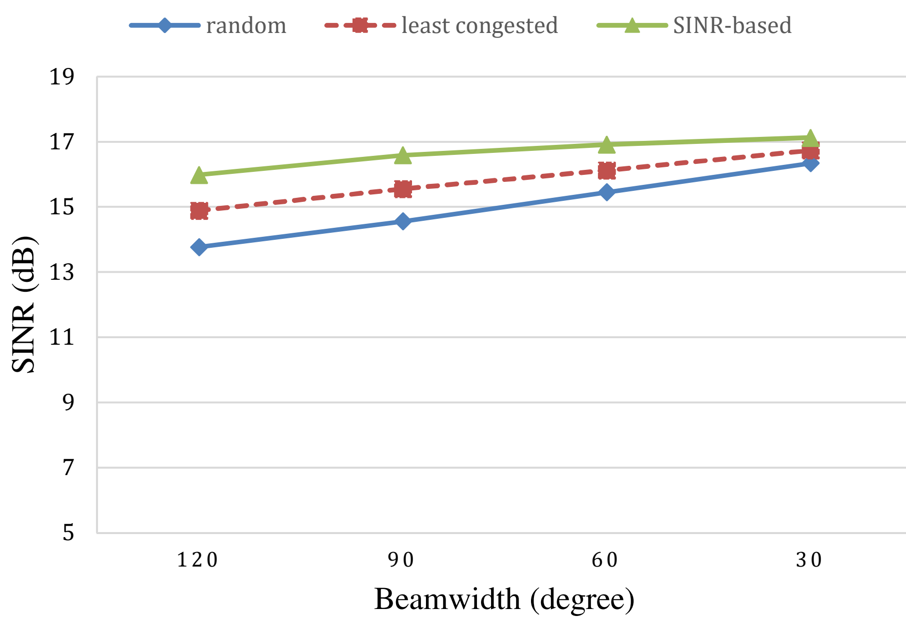
Moreover, as the vehicle density increases, the gap of the SINR values between the least congested SCH selection and the random SCH selection. The reason is that the number of vehicles that can interfere toward the service provider increases as the vehicle density increases.

However, the proposed SINR-based directional MAC protocol significantly outperforms the two methods. The reason is that the service provider is able to determine to select the SCH number that can maximize the lowest SINR. Therefore, whenever new prospective service provider intends to select a SCH number, it can minimize deteriorating effect on the system by selecting the SCH number.

Secondly, the beamwidth of the directional antenna is narrowed down to 30˚ from 60˚. When the beamwidth is set to 30˚, the average SINR values increased compared to the case of 60˚ no matter what methods are applied as shown in Figure 19 (b). The reason why the overall average SINR values increased is because the narrower the beamwidth is, the smaller the area that is interfered. Thus, a service provider can focus on its target vehicle and reduce the unnecessary interferences to neighbor vehicles. At the same time, the trend of the three methods is similar to the previous case that the beamwidh is 60˚. The least congested SCH selection method outperforms the random SCH selection method as the vehicle density decreases. Moreover, the SINR value gap between the least congested SCH selection and the random SCH selection get closer. However, the SINR-based method significantly outperforms the two methods even if the vehicle density increased. Therefore, it can be concluded that the narrower beamwidh and the lower vehicle density can improve the system performance.



(a) Vehicle density $\sigma = \frac{1}{30^2}$

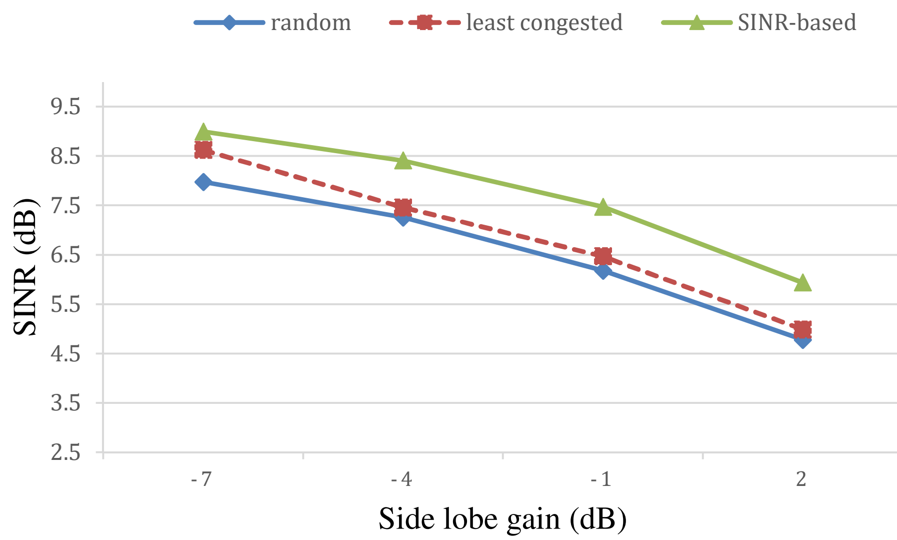


(b) Vehicle density $\sigma = \frac{1}{60^2}$

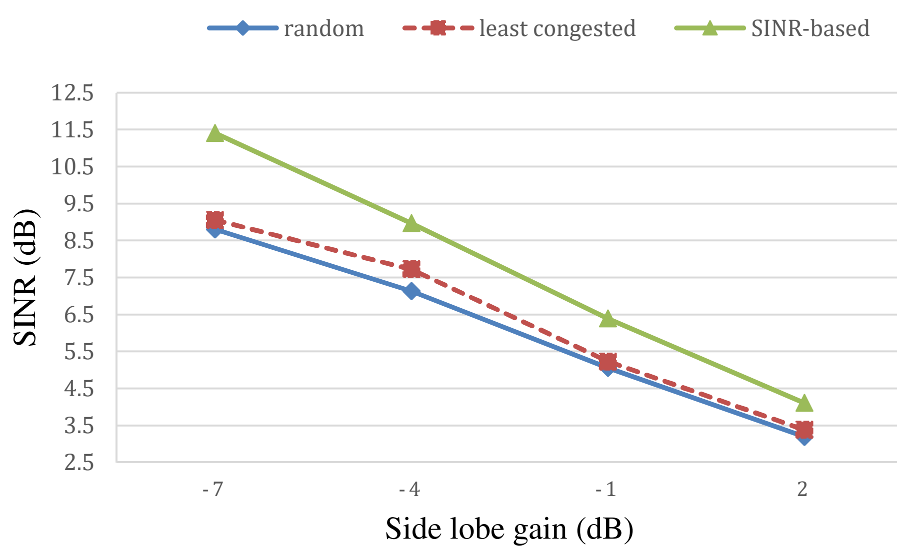
Figure 20: Average SINR of vehicles vs Beamwidth

Thirdly, as shown in Figure 20 (a), the average SINR values degrease in the three methods as the beamwidth increases. When the vehicle density $\sigma = \frac{1}{30^2}$, the performance gain of the least congested SCH selection method is 0.9% higher than the random SCH selection method. However, the SINR-based approach significantly outperforms the two methods. The performance gain of the SINR-based approach is 20% higher than the least congested SCH selection method. In the vehicle density $\sigma = \frac{1}{60^2}$, which is lower density than $\sigma = \frac{1}{30^2}$, the overall average SINR values increased as shown in Figure 20 (b). The performance gain of the least congested SCH selection method 5.4% higher than the random SCH selection method. On the contrary, the performance gain of the SINR-based approach is 7.9% higher than that of the least congested SCH selection. Since the vehicle density $\sigma = \frac{1}{60^2}$ is lower than $\sigma = \frac{1}{30^2}$, the expected number of vehicles that are in the main lobe of the directional antenna of the service provider also gets lower. As the beamwidth gets narrower, the average SINR values increased. Likewise, the average SINR values get lower as the beamwidth gets larger because the expected vehicles that can be interfered by the main lobe of the service provider can be greater. This observation indicates that the narrower beamwidth can improve the performance. Especially in the higher vehicle density area, it is demonstrated that the narrower beamwidth can increase performance gain using the proposed SINR-based approach.

Fourthly, the simulation is conducted to investigate how the side lobe gain power can affect the overall average SINR values of the vehicles. As shown in Figure 21 (a), the overall average SINR values decreased as the side lobe gain power increases.



(a) Vehicle density $\sigma = \frac{1}{30^2}$, Beamwidth: 30°

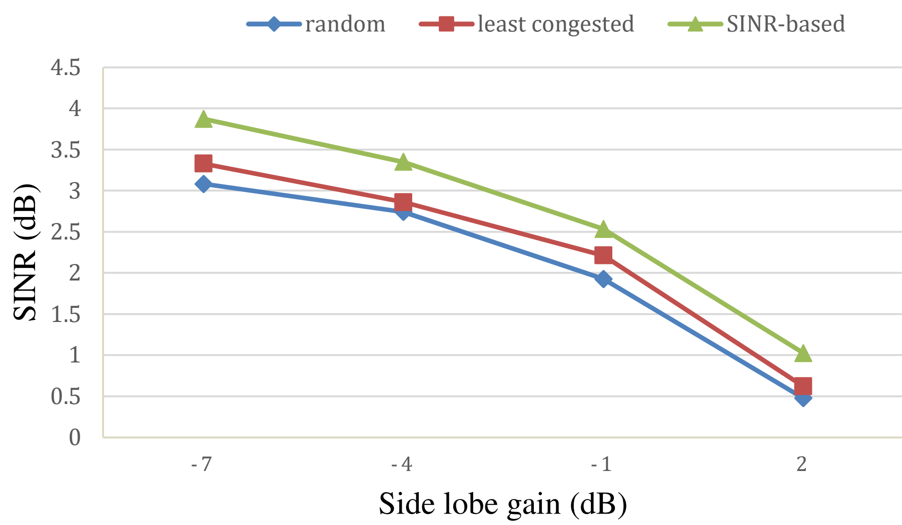


(b) Vehicle density $\sigma = \frac{1}{10^2}$, Beamwidth: 30°

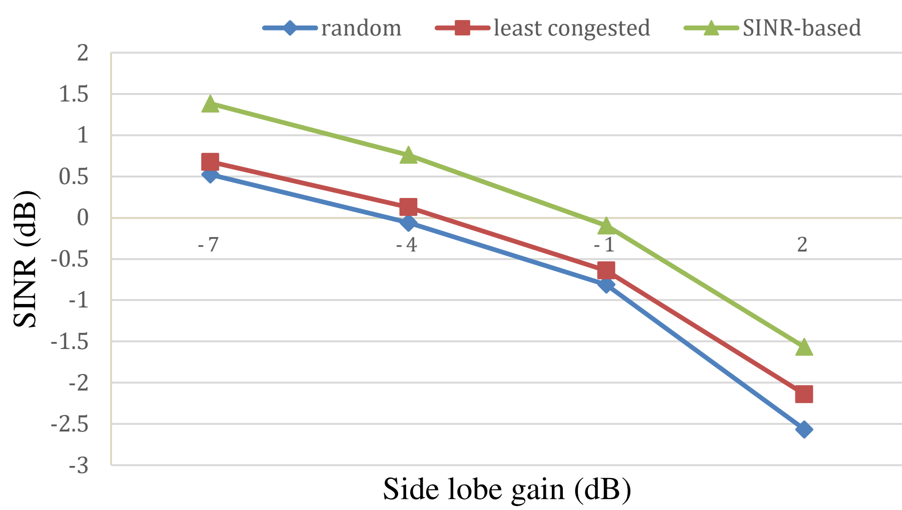
Figure 21: Average SINR of vehicles vs Side lobe gain power

The reason is that the directional antenna gain of the receiver, G_r increases the unwanted signal power, which is interference. Unlike the most existing directional MAC protocols that neglect the side lobe gain power, the proposed directional MAC protocol considers the influence of the side lobe gain power of the directional antennas. As the side lobe gain power increases, the received power from all the directions except the beamwidth, which is interference increases. The least congested SCH selection method outperforms the random SCH selection as high as 4.9%. The SINR-based approach outperforms the least congested SCH section method as high as 12.1%. Thus, the SINR-based approach significantly improve the performance compared to the other two methods. When the vehicle density increased to $\sigma = \frac{1}{10^2}$, if the side lobe gain power increases up to 2dB, then the overall average SINR decreases drastically down to 3 to 4dB. The reason is that the higher density caused vehicles to be near the service user. In addition, the greater side lobe gain power increased the received power, which acts as interference to the service user.

Fifthly, as shown in Figure 22 (a), the beamwidth of the directional antenna increased compared to Figure 21. If the vehicle density is constant, the greater beamwidth reduces the overall average SINR values. The reason is that if the beamwidth is larger, the probability of that there exist the vehicles that can interfere and also can be interfered is higher. Figure 22 (b) shows that if the beamwidth is as large as 120° and the side lobe gain power is greater than -1 dB, then the average SINR values go negative. However, the negative SINR values are still higher than the SINR outage value -6.36 [dB], which was calculated in equation (16).



(a) Vehicle density $\sigma = \frac{1}{40^2}$, Beamwidth: 60˚



(b) Vehicle density $\sigma = \frac{1}{40^2}$, Beamwidth: 120˚

Figure 22: Average SINR of vehicles vs Side lobe gain power

5.4 Conclusions

In this Chapter, a novel SINR-based Directional MAC (SDMAC) protocol for the IEEE 1609.4 multi-channel vehicular ad-hoc networks is designed and demonstrated. The SDMAC protocol can increase the overall SINR by maximizing spatial reuse and reducing interference in IEEE 1609.4 multichannel environment. Since the WSA message of the current IEEE 1609.4 standard does not include direction information, not only the SCH number but also the direction information is piggybacked into the BSM. Having the direction information, the service providers increased concurrent transmissions in the multichannel environment. Through extensive simulations, the SINR-based approach outperformed the least congested SCH number selection method and the random SCH selection method. One of the distinguishing contribution of the SDMAC is to consider the side lobe gain power of the directional antenna, which cannot be neglected.

CHAPTER VI

CONCLUSIONS AND FUTURE RESEARCH

6.1. Conclusions

6.1.1 Contributions

The objective of this research is to design novel and efficient service channel utilization methods for the IEEE 1609.4 multi-channel vehicular ad hoc networks. This dissertation has contributed three techniques that can maximize the number of concurrent transmissions of vehicles in the unique multi-channel environments for three cases.

- Broadcast transmissions using the Omnidirectional antennas
- Unicast transmissions using the Omnidirectional antennas
- Unicast transmissions using the Directional antennas

First, the proposed solution improved the packet reception ratio (PRR) of the service providers by mitigating the hidden node problem, leading to improvement of the wireless network system. The current IEEE 1609.4 standard is unable to prohibit hidden service providers from using the same SCH, which will lead to the hidden terminal problem. Therefore, this dissertation proposed a novel scheme that enables a service provider to avoid selecting the same SCH as nearby hidden service providers had already selected. Through extensive simulations, it is demonstrated that this proposed approach has average 13% to 23% higher PRR than the random SCH way in broadcast scenarios under the IEEE 1609.4 multi-channel environment.

Secondly, the proposed solution improved the average throughput and reduced the medium access delay of the wireless network system. Unlike the CCH, the SCH allows the vehicles to trigger the RTS/CTS/data/ACK handshake in order to transmit large size of data without the hidden node problem. The proposed protocol enabled a service provider to transmit in parallel while performing the RTS/CTS handshake during the SCH interval. By piggybacking the candidate SCH number in the optional field of the BSM defined by the SAE J2735 standard, a service provider can determine the final SCH number that does not overlap with its exposed node's one. As a result, the service provider can avoid selecting the same SCH, and thus they do not need to defer their medium access in the same SCH, leading to concurrent transmissions. Throughout extensive simulations, it is verified that this proposed method reduced the medium access delay and improved the average throughput performance by up to 26% compared to the random SCH selection in the IEEE 1609.4 multi-channel unicast scenarios.

Thirdly, this dissertation further developed the distributed SCH selection scheme and extended the unicast transmissions into the directional antenna environments. The proposed method can increase the overall SINR by maximizing spatial reuse and reducing interference in IEEE 1609.4 multichannel environment. Since the WSA message of the current IEEE 1609.4 standard does not include direction information, selecting the least congested SCH number does not guarantee the best performance. Moreover, most existing MAC protocols for directional antennas assume ideal directional antennas with the negligible side lobe gain power, which is unrealistic. However, the proposed SINR-based Directional MAC (SDMAC) protocol for the IEEE 1609.4 multi-channel vehicular ad-hoc networks significantly improve the overall average SINR of the vehicles with realistic directional antennas with even considerable side lobe gain power. Through extensive simulations, the SDMAC incorporated with the multichannel is verified to significantly improve the overall average SINR of the vehicles with realistic directional antennas with even considerable side lobe gain power.

6.1.2 Future Research

By exploiting the optional field of the basic safety message, this dissertation could mitigate the hidden node problem in broadcast scenarios and the exposed node problem in unicast scenarios. Using the technique, a service provider can broadcast its service to as many service users as possible by reducing a packet collision and also can improve the throughput performance by reducing the channel access time during the service channel intervals.

However, the limitation of this dissertation is that it concentrated on only vehicle-to-vehicle (V2V) networks. Therefore, the future research will focus on vehicle-to-roadside (V2R) networks, where a Road-Side Unit (RSU) has a much longer transmission range than an On-Board Unit (OBU). If the RSU is located beyond the transmission range of the OBU, the OBU can receive from the RSU but the RSU cannot receive from the OBU. Thus, the *intermediary receiver* that was defined in the preliminary research cannot take the active role in V2R networks because its signal cannot reach the RSU. Therefore, building upon this dissertation conducted, a new protocol will be designed to solve the hidden node problem in V2R networks, where gain is asymmetric. When an RSU is beyond the transmission range of an OBU, SCH number selection information obtained by the OBU will be conveyed to the RSU in multi-hop way. The approach can be proactive or reactive.

To be *proactive*, therefore, the OBU should forward the service channel selection information immediately after the OBU obtains it from the hidden service provider of the RSU. To be *reactive*, however, the OBU delivers the obtained service channel selection information only if the RSU selects the same service channel as its hidden service provider. The two approaches will be intensively compared against each other and analyzed numerically.

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